

**Automatic Pacing:
On the use of external timing cues to regulate
speed during human walking and running**

by

Mark Snaterse

M.Sc., VU University, 2008

B.Sc., VU University, 2006

Dissertation in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

in the

Department of Biomedical Physiology and Kinesiology
Faculty of Science

© Mark Snaterse 2014

SIMON FRASER UNIVERSITY

Spring 2014

All rights reserved.

However, in accordance with the *Copyright Act of Canada*, this work may be reproduced, without authorization, under the conditions for "Fair Dealing." Therefore, limited reproduction of this work for the purposes of private study, research, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.

Approval

Name: Mark Snaterse

Degree: Doctor of Philosophy

Title of Thesis: *Automatic Pacing:
On the use of external timing cues to regulate speed
during human walking and running*

Examining Committee: **Chair:** Damon Poburko
Assistant Professor

J. Maxwell Donelan
Senior Supervisor
Associate Professor
Biomedical Physiology and
Kinesiology

Arthur D. Kuo
Supervisor
Professor
Dept. of Mechanical Engineering
University of Michigan

Stephen N. Robinovitch
Supervisor
Professor
Biomedical Physiology and
Kinesiology

David C. Clarke
Internal Examiner
Assistant Professor
Biomedical Physiology and
Kinesiology

John Bertram
External Examiner
Professor
Dept. of Cell Biology and Anatomy
University of Calgary

Date Defended/Approved: December 16, 2013

Partial Copyright Licence



The author, whose copyright is declared on the title page of this work, has granted to Simon Fraser University the non-exclusive, royalty-free right to include a digital copy of this thesis, project or extended essay[s] and associated supplemental files (“Work”) (title[s] below) in Summit, the Institutional Research Repository at SFU. SFU may also make copies of the Work for purposes of a scholarly or research nature; for users of the SFU Library; or in response to a request from another library, or educational institution, on SFU’s own behalf or for one of its users. Distribution may be in any form.

The author has further agreed that SFU may keep more than one copy of the Work for purposes of back-up and security; and that SFU may, without changing the content, translate, if technically possible, the Work to any medium or format for the purpose of preserving the Work and facilitating the exercise of SFU’s rights under this licence.

It is understood that copying, publication, or public performance of the Work for commercial purposes shall not be allowed without the author’s written permission.

While granting the above uses to SFU, the author retains copyright ownership and moral rights in the Work, and may deal with the copyright in the Work in any way consistent with the terms of this licence, including the right to change the Work for subsequent purposes, including editing and publishing the Work in whole or in part, and licensing the content to other parties as the author may desire.

The author represents and warrants that he/she has the right to grant the rights contained in this licence and that the Work does not, to the best of the author’s knowledge, infringe upon anyone’s copyright. The author has obtained written copyright permission, where required, for the use of any third-party copyrighted material contained in the Work. The author represents and warrants that the Work is his/her own original work and that he/she has not previously assigned or relinquished the rights conferred in this licence.

Simon Fraser University Library
Burnaby, British Columbia, Canada

revised Fall 2013

Ethics Statement



The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

- a. human research ethics approval from the Simon Fraser University Office of Research Ethics,

or

- b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University;

or has conducted the research

- c. as a co-investigator, collaborator or research assistant in a research project approved in advance,

or

- d. as a member of a course approved in advance for minimal risk human research, by the Office of Research Ethics.

A copy of the approval letter has been filed at the Theses Office of the University Library at the time of submission of this thesis or project.

The original application for approval and letter of approval are filed with the relevant offices. Inquiries may be directed to those authorities.

Simon Fraser University Library
Burnaby, British Columbia, Canada

update Spring 2010

Abstract

Out of all parameters used to describe gait, overground speed is one of the most important. The importance of gait speed is highlighted when used as a measure of performance during exercise, or as a measure of function when walking ability is compromised. Because the ability to control gait speed is imperative to reach optimal results in both exercise and gait rehabilitation, a system that helps people to control their overground speed more accurately might be beneficial. Developing an overground speed control system was the main goal of this thesis. To gain insight in the performance enhancing effects that can be expected from such a system, my colleagues and I first determined the ability of recreational runners to accurately control their own speed. We then used a simulation approach to estimate the effect of pacing inaccuracy on optimal running performance. Our simulation results suggested that the existing pacing error ($2.3 \pm 4.6\%$) would decrease optimal performance by approximately 5% for an average recreational runner. These results indicate that the performance of recreational runners could be improved by minutes for typical race distances, simply by helping them achieve and maintain their optimal speed. To determine the viability of controlling overground speed by prescribing step frequency, we quantified the dynamic response in walking and running speed following controlled perturbations in prescribed metronome frequency. We found that perturbations in metronome frequency triggered rapid and predictable changes in speed, suggesting that overground speed is indeed controllable by prescribing step frequency. However, due to the variability present in the speed response, both within and between individuals, accurately controlling overground speed using an *open-loop* speed control system is not possible. To improve speed control performance we developed and built a *closed-loop* speed control system, which made the metronome frequency directly dependent on the instantaneous speed error. We tested the performance of this system in both walking and running, and found that the speed control accuracy of a closed-loop system was significantly better compared to self-paced running and an open-loop speed control system. Finally, we translated the speed control system into a training tool available to the general public.

Keywords: Locomotion; pacing; real-time control; auditory rhythmic stimulation; research and development;

Acknowledgements

The last five years would not have been the same without a number of great people. I would like to take this space to say thanks to everyone, in no particular order.

None of the work presented in this thesis would have been possible without the help from the many volunteers that participated in my studies. I am very thankful for your time and energy, and simply for meeting all of you.

Max, it has been a great pleasure to work under your supervision. The learning opportunities you have provided extent far beyond scientific training. I am especially thankful for the room you gave me to pursue my dreams outside the academic world. I am excited to see where you will take your research, and look forward to continue collaborating in the future. All the best for you and your family!

My time at SFU would have been very different without my lab mates and other school friends. Thanks so much for the many good and bad hours we have spent together, and the fun, inspiring and educational conversations we have had. I wish the best for all of you, and hope that our paths will cross again soon.

A large part of my time in Vancouver was dedicated to exploring the Coast Mountains, both on skis and on foot. I am grateful for all the good friends I have met on these adventures. A special thanks goes out to Ben, Saar and James for mentoring me in this, for me, largely unknown environment. I look forward to many more adventures together, wherever it might be!

Mom, dad, brother—thanks for the huge support I received from you, both during the last few years and before. I am incredibly grateful that you respected any of my decisions, but also provided subtle pushes in the right direction at important times. Without these pushes I don't think I would be writing this right now. Thank you!

The same, and so much more, I can and should say to Rianne. The remaining space on this page is not enough to say how glad I am that you joined me on this adventure across the ocean, how thankful I am for your support throughout, and how proud I am of your achievements. I am excited to see what the future holds for us, and am confident that we will make the very best of it together!

Table of Contents

Approval.....	ii
Partial Copyright Licence.....	iii
Ethics Statement.....	iv
Abstract.....	v
Acknowledgements.....	vi
Table of Contents.....	vii
List of Tables.....	x
List of Figures.....	x

Chapter 1. Introduction	1
Motivation.....	2
Benefits of improved pacing in running.....	2
Benefits of improved pacing in walking.....	3
Using rhythmic pacing to control movement.....	4
Effects of auditory rhythmic pacing during exercise.....	5
Effects of auditory rhythmic pacing during walking rehabilitation.....	7
Existing methodologies employing rhythmic pacing	8
Physiological requirements for accurate speed control using rhythmic pacing.....	10
Open-loop vs. closed-loop control of overground speed	11
Aims 13	

Chapter 2. Effect of pacing error and variability on the optimal performance of recreational runners	14
Abstract.....	14
Introduction.....	14
Methods.....	16
Experiment.....	16
Simulations	20
Results.....	22
Experiment.....	22
Simulations	24
Discussion.....	27

Chapter 3. Dynamic response in walking and running speed following changes in prescribed step frequency	33
Abstract.....	33
Introduction.....	34
Methods.....	37
Experimental setup	37
Experimental protocol	38
Data analysis	39
Statistics.....	44
Results.....	45

Steady-state relationship	47
Dynamic response	48
Discussion.....	51
Chapter 4. Development and testing of a feedback controlled metronome for the accurate control of walking and running speed	57
Abstract.....	57
Introduction	58
Methods	59
Speed control system design	59
Experiments	60
Results	63
Accuracy	63
Responsiveness.....	64
Robustness	65
Stability	66
Comfort	67
Discussion.....	67
Chapter 5. From idea to product	73
Abstract.....	73
Introduction	73
Transitioning from research to development to product.....	74
Developing the smartphone application.....	76
Dealing with low quality speed measurements	77
Dealing with a real-life run (which is not just running).....	79
Dealing with large perturbations	80
Using music instead of a metronome.....	80
Testing the application	83
Early development phase	83
Late development phase.....	84
Scientific experiment to determine application's performance	85
Current application	85
Functionality	86
Run modes.....	86
Media attention and user reviews	87
Future improvements	88

Chapter 6. Conclusion..... 90

References 93

Appendix A. Running self-pacing questionnaire 103

Appendix B. Closed-loop speed control system design 104

Appendix C. Closed-loop speed control questionnaire..... 121

Appendix D. Methods and Systems for Control of Human Locomotion..... 124

List of Tables

Table 4.1	Individual controller settings for speed control system	120
-----------	---	-----

List of Figures

Figure 1.1	General control diagrams	12
Figure 2.1	Experimental setup	17
Figure 2.2	Pacing error and variability definitions	20
Figure 2.3	Relationship between running speed and time to exhaustion	21
Figure 2.4	Example time-series data	22
Figure 2.5	Pacing error results	23
Figure 2.6	Modeling of the pacing variability distribution	25
Figure 2.7	Example results of Monte Carlo simulations	26
Figure 2.8	Monte-Carlo simulation results	26
Figure 3.1	Experimental setup and time series data of the experimental protocol.....	39
Figure 3.2	Two-process system and possible responses	41
Figure 3.3	Estimating noise from the data	43
Figure 3.4	Bootstrap procedure	45
Figure 3.5	Frequency-speed relationship for all participants	46
Figure 3.6	Step frequency-speed relationship slope	47
Figure 3.7	Average speed responses to changes in metronome frequency.....	48
Figure 3.8	Dynamics of the speed response to changes in metronome frequency.....	49
Figure 3.9	Amplitude of the fast speed response to changes in metronome frequency.....	50
Figure 3.10	Controlling speed of a person with a fast versus a slow response	53
Figure 4.1	Experimental setup and time series data of the experimental protocol.....	62
Figure 4.2	Speed error	64
Figure 4.3	Speed response dynamics	65
Figure 4.4	Example result for incorrectly tuned control system: oscillation	66
Figure 4.5	Example result for incorrectly tuned control system: instability	67
Figure 4.6	Effect step-length perturbation on controlled speed	69
Figure 4.7	Effect of hill perturbation on controlled speed.....	70
Figure 4.8	Effect of speed control system on maximum running performance.....	72
Figure 5.1	Running speed measurements using smartphone	79
Figure 5.2	Example tempo distribution of songs in tester's music libraries	83
Figure 5.3	Example speed control results.....	85

Figure 5.4	Example sensor fusion results	89
Figure 6.1	Example heart rate control results	91

Chapter 1. Introduction

The recent explosion of wearable computing will likely be the start of a new era for biomedical engineers, kinesiologists, coaches and health workers. Already, over 60 percent of American's carries a device capable of measuring important health and exercise related information such as activity level (e.g. steps taken per day), vital signs (i.e. heart rate and breathing rate), and stress level (e.g. through heart rate variability). In the next few years we will likely see significant advancements in sensor and display technologies, further increasing the possibilities to collect and present data. Although the ability to measure all sorts of data might be useful in itself, the goal of these measurements is ultimately to shape people's behaviour, for example by setting daily activity goals or by recommending relaxation exercises when stress levels increase. My research is focused on the ability to influence people's behaviour in real-time using signals that are directly related to what they are doing. For example, vibration, light or sound could be used to deliver *control signals* to individuals to guide them towards a desired behaviour.

The main purpose of this thesis is to explore the possibilities of controlling walking and running speed indirectly by prescribing movement tempo using sound (*auditory rhythmic pacing*). My hope is that this thesis might serve as a template for designing systems to control people's behaviour in real-time. First, I will demonstrate that there is a problem that might be solvable through real-time control of people's behaviour. Second, I will determine whether it is possible to have the required control authority to solve this problem. Third, I will develop a control system to solve, or at least reduce, this problem. Fourth, I will test the performance of this system. And finally, I will describe how I transferred the ideas described in this thesis into a training tool that is now used by people across the world.

Motivation

Out of all parameters used to describe gait, overground speed is one of the most important as it determines the time required to cover a given distance. The importance of gait speed is highlighted when used as a measure of performance during exercise, or as a measure of function when walking ability is compromised^{1,2}. In the following I will discuss the potential benefits of an overground speed control system in both exercise and gait rehabilitation.

Benefits of improved pacing in running

A system for accurately controlling overground speed could be beneficial for a variety of different reasons in running. First, the ability to achieve and maintain a predetermined target speed is a prerequisite for achieving optimal running performance. For example, in long distance events it is believed that maintaining a constant speed throughout the is ideal^{3,4}. However, recent work has suggested that especially recreational runners are not very accurate when it comes to controlling their running speed (*pacing*)⁵. Hence, a system for accurately controlling overground running speed could potentially help recreational runners to improve their performance, simply by helping them achieve and maintain their target speed.

Second, a system for controlling running speed could be beneficial when performing interval training, a popular training regime where bouts of running at high speeds are interspersed with periods of running at lower speeds⁶. The speed control system could be used to guide a runner through their interval protocol with high accuracy. This would be especially useful on unmeasured courses, where distance information is not readily available. Furthermore, if rhythmic pacing can indeed be used to accurately control speed, runners could be guided through their interval workout in a user-friendly way, without any other requirements than to synchronize their steps to the prescribed rhythm.

Finally, a system that accurately controls overground speed could serve as a motivational aid during running. As long as the runner synchronizes their steps with the rhythmic stimulus, they know that they are maintaining their desired pace. Each time the runner lets their speed drop, the speed control system will pick up the tempo of the stimulus to bring the runner back to their desired pace. Thus, the speed control system

could be a 'virtual running partner', potentially motivating the runner to go a little faster or further.

Benefits of improved pacing in walking

A system for controlling overground walking speed could potentially be useful in gait rehabilitation as a means to improve gait speed. As gait speed is strongly related to function and quality of life in patients suffering from stroke^{1,2,7} or Parkinson's disease^{8,9}, improvement of gait speed is one of the key goals in rehabilitation from these neurological diseases^{10,11}. In fact, improvement of gait is the number one rehabilitation goal for many hemiparetic stroke patients¹². A guiding principle in rehabilitation from neurological diseases is that a skill will improve if it is practiced¹³. Hence, to improve walking speed patients will need to practice their gait speed¹³. Indeed, it was recently shown that walking speed after stroke improved significantly more following aerobic fitness training, performed through speed-dependent training on a treadmill, than following conventional gait therapy consisting of a combination of Bobath and proprioceptive neuromuscular facilitation¹⁴. In a comparable study on the immediate effects of speed-dependent treadmill training on walking speed following Parkinson's disease significant improvement in walking speed was found for both progressive speed and constant speed treadmill training, but not for conventional gait therapy consisting of proprioceptive neuromuscular facilitation¹³. These positive effects of progressive speed treadmill training on Parkinson's patients walking speed were confirmed in two recent studies^{15,16}.

If it would be possible to accurately control speed, progressive speed training could potentially be performed overground. This would have a number of benefits compared to performing this type of training on a treadmill. First, performing (part) of the fitness training overground would result in increased task specificity, as the goal of any attempts to improve post-stroke walking ability is improved overground walking. Indeed, it was recently proposed that the ideal rehabilitation program would include not just treadmill walking, but also overground walking¹⁷. Second, as the overground speed control system would be implemented using auditory rhythmic pacing, users would simultaneously benefit from the effects of rhythmic pacing on post-stroke walking (discussed below). Finally, since an overground speed control system as discussed here could be implemented in existing wearable computers such as watches or smartphones,

it would enable patients to perform speed training outside the clinical setting. This might potentially stimulate retention of rehabilitation effects, thereby improving functional walking ability.

Although in this section I have focused on rehabilitation from stroke and Parkinson's disease, treadmill training has shown positive effects in other neurological diseases affecting walking ability, such as cerebral palsy¹⁸ and multiple sclerosis¹⁹. Hence, beneficial effects of an overground speed control system might exist for individuals suffering from other sources underlying gait disability as well.

Using rhythmic pacing to control movement

In this thesis I will specifically explore the possibilities of using *auditory rhythmic pacing* to accurately control overground walking and running speed. Using auditory rhythm to control movement tempo is not a new idea. In fact, the indications of an intricate relationship between movement and music can be found in the Egyptian hieroglyphs, the Babylonian epic Gilgamesh (one of the earliest surviving works of literature) and is even believed to have existed in hunter communities in the Palaeolithic era²⁰. More well known, 'modern day', examples are the use of drums to coordinate strokes during rowing, and marching music to orchestrate the movements of large bodies of soldiers.

Perhaps the main reason that auditory rhythm is used extensively to control movement is the highly intuitive nature of synchronizing movements to rhythmic stimuli. This synchronization often occurs spontaneously²¹, and can even be hard to suppress. The tendency of people to tap their finger or feet with music is one common example. Evidence that the relationship between movement and auditory rhythm develops very early in humans was provided by Phillips-Silver & Trainor²², who demonstrated that human infants as young as 7-months of age preferred music with a tempo at which they had previously been bounced. Furthermore, 5-month olds display spontaneous rhythmic motion when music is played²³. Although infants this young show some flexibility in their rhythmic movement—faster music tempo results in faster movement—usually their movements are not fully synchronized with the music. This ability, to actually synchronize movements with simple auditory rhythmic stimuli, appears to be fully develop by the age of five²⁴.

A second reason for the popularity of using rhythmic stimuli to prescribe movement tempo might be the fact that it is a source of positive affect. Already in infants as young as 5-months of age a positive correlation was found between the synchronization accuracy of their movements to music, and the duration of smiles²³. The main effect underlying the increased positive affect when moving to rhythmic stimuli is believed to be increased endorphin release²⁵. By studying the effect of music on perceived pain, Dunbar²⁶ presented evidence that this increased endorphin release is only present during active performance of music—including dancing—but not when merely listening to music. A similar effect of synchronized movement has been found during rowing, where it was shown that training in synchrony with team members increased the pain threshold over training alone²⁷. Although it has been shown that music activates brain regions associated with motor function²⁸ and emotion^{29,30}, the exact neural mechanisms responsible for the relationship between rhythmic stimuli, movement and endorphin release, and the origin of this relationship is currently unknown³¹.

The effect of synchronizing movement to rhythmic stimuli has been studied extensively in both exercise and rehabilitation research. In the following I will provide an overview of the current knowledge regarding the effects of rhythmic pacing in both these domains.

Effects of auditory rhythmic pacing during exercise

Synchronizing movements to rhythmic stimuli during exercise, such as moving in synchrony with music, has been shown to have positive psychological (e.g. improved mood), psychophysiological (e.g. reduced perceived exertion) and ergogenic (i.e. performance enhancing) effects^{32,33}. Some of these effects have also been found when using asynchronous music. But most effects, especially the psychological and ergogenic ones, are larger when using synchronous music³³.

An example of the psychological effect of rhythmic pacing is the finding that it improves mood during exercise. Hayakawa and colleagues³⁴ studied the effect of no music, asynchronous Japanese folk songs, and synchronous aerobic dance music on measures of mood such as vigour, depression, confusion and tension. They found that both the asynchronous and synchronous music had a positive effect on mood, but that the synchronous music had a significantly stronger effect. More specifically, they found a

50% increase in reported vigour and 80% decrease in reported confusion when using synchronous music compared to asynchronous music.

Although the performance enhancing effects of asynchronous music are still subject of debate, the effects of synchronous music on performance are well established³². For example, it was shown that synchronous music reduced time to completion during a 400-meter sprint³⁵, as well as time to exhaustion during treadmill walking³⁶ and treadmill running³⁷. The nature of the music seems less important to trigger this positive effect than the simple fact that it is synchronized to the movement. Except in the study on treadmill walking³⁶, no difference was found between the use of motivational or neutral music in the previously mentioned studies (in all these studies motivational quality of songs was determined using the Brunel Music Inventory Rating-2 scale, a scale designed to assess motivational qualities of music in exercise³⁸). The suggestion that the motivational quality of music is not the main factor underlying performance improvements when exercising to music was further supported by a recent study, where it was found that a simple metronome provided a comparable performance increase as motivational music³⁹.

It has been suggested that the improved performance when synchronizing steps to rhythmic stimuli during treadmill running is a result of increased running economy^{37,39}, although as far as I am aware this idea is not well established. Also, this effect is unlikely to hold during overground running. In fact, it has been shown that the amount of energy required to cover a certain distance at a particular speed will increase while synchronizing steps to a rhythmic stimulus compared to unconstrained running⁴⁰. This is a consequence of the existence of different energetically optimal relationships between step frequency, step length and speed dependent on which of these three gait characteristics is constrained⁴¹. The step frequency that people select to run at a specific speed is different when synchronizing their steps to a rhythmic stimulus compared to speed constrained running, resulting in an increased energetic cost to run at a specific speed when steps are synchronized. This is a potential disadvantage of using rhythmic pacing to control speed, as it might reduce the positive effects of improved speed control in certain conditions.

Effects of auditory rhythmic pacing during walking rehabilitation

Auditory rhythmic pacing has specific positive effects on walking in people suffering from various neurological diseases compromising walking ability. The most well studied cases are the use of rhythmic pacing during rehabilitation from stroke and Parkinson's disease.

The benefits of rhythmic pacing on post-stroke walking were first shown by Thaut and colleagues⁴², who found that rhythmic pacing resulted in improved stride symmetry, improved use of the affected limb, and decreased EMG-activity in the affected limb during swing phase. In follow-up studies a number of other benefits were found, such as increased symmetry in hip range of motion⁴³, and increased walking speed⁴⁴.

Similar positive effects of rhythmic pacing have been found in Parkinson's patients. It has been demonstrated in a range of different studies that rhythmic auditory pacing increases step frequency and step length—and thus walking speed—compared to self-paced walking⁴⁵⁻⁴⁸. A plausible explanation for the positive effects of rhythmic pacing in Parkinson's patients appears to be the tight coupling between the auditory and motor areas in the brain²⁸. The results of work by Jahanshahi et al.⁴⁹ and Cunnington et al.⁵⁰ indeed suggest that triggering movement using auditory stimuli offers an alternative pathway for movement initiation, which is less affected by the dopamine shortage in the basal ganglia underlying Parkinson's disease compared to internally triggered movements. The beneficial effect of rhythmic pacing on walking appears to highlight the notion that Parkinson's patients generally react better than they act⁴⁹.

Because one of the proposed benefits of the speed control device developed here is the accessibility outside the clinical settings—and thus outside professional supervision—the safety aspect of rhythmic pacing is highly relevant. Recent research has offered a first insight into the safety of using rhythmic pacing in the rehabilitation context. One potential downside of rhythmic pacing during gait rehabilitation is that it increases intentional demands over regular walking⁵¹, perhaps increasing the potential for falls. However, a recent study addressing the safety of using music for gait training outside the clinical setting concluded that the use of music did not increase the risk of falling in Parkinson's patients⁵². Furthermore, work by Nieuwboer and colleagues⁵³ suggested that rhythmic pacing might actually decrease the risk of falling in Parkinson's patients, and increase confidence in patients that they will not fall. These results suggest that rhythmic pacing

can be applied safely in the rehabilitation context, at least when falls are the main concern.

Existing methodologies employing rhythmic pacing

As illustrated in the previous discussion, the large majority of the identified effects of rhythmic pacing during exercise and rehabilitation are positive. Thus, it might not come as a surprise that a number of methodologies, other than plain metronomes, have been described to leverage these positive effects.

One methodology that has received considerable attention is to automatically synchronize music to the current movement tempo of the user. This methodology has been implemented in a variety of systems such as JoMP⁵⁴, D-Jogger⁵⁵ and moBeat⁵⁶. These systems all capture the user's step frequency through use of accelerometers⁵⁷. They then either select songs closest to the current step frequency, or actually change the tempo of the song through time-stretching to more accurately match the current step frequency⁵⁸. The result is that the user is always moving in synchrony with their music. Although the actual benefits of this methodology on exercise performance is currently unknown, results of questionnaires suggest that users enjoyed the exercise more when using any of the systems mentioned above⁵⁴⁻⁵⁶.

The idea of using rhythmic pacing to enhance exercise performance has been taken one step further in Yamaha's BODiBEAT, Microsoft's TripleBeat⁵⁹ and Philips' IM4Sports⁶⁰. In these systems the music is not only synchronized to the user's step frequency, but is actually used to control user's running intensity. The idea is that as long as users synchronize their steps to the music, the music will attempt to drive their heart rate to the target heart rate. This is an example of real-time control of people's behaviour discussed earlier. If this methodology can indeed be used to accurately clamp user's heart rate to their desired heart rate, this would be a major improvement over the current standard for maintaining users at their desired intensity. The current standard is to play beeps whenever the user's heart rate is outside the predefined range. The tone or frequency of the beep indicates whether the user's heart rate is too high or too low—users then have to guess by how much to speed up or slow down to return to their desired intensity. In comparison, if music can indeed be employed to keep runners at their target intensity, all users would need to do is to synchronize their steps to the beat of the music. As far as I

am aware, the studies by Oliver & Kreger Stickles⁶¹ and Oliveira & Oliver⁵⁹ have been the only attempts to demonstrate the actual performance of using music to control exercise intensity. Although the results were promising (TripleBeat managed to maintain user's in their target zone 83% of the time), I have significant concerns regarding the studies responsible for these findings. For example, participants were allowed to check their current and target heart rate on a display, enabling conscious pace adjustments to maintain the desired intensity. Furthermore, TripleBeat's accuracy was reported based on a protocol in which the system was used to keep participant's heart rate within a single target zone, which was their self-selected, preferred heart rate zone. Hence, it is not clear how the system would perform in a protocol with varying heart rate targets, while participants are ignorant of their current performance. The results of this thesis will provide further insight into the performance that can be expected when using rhythmic pacing to control heart rate during running, as running speed and heart rate are strongly coupled⁶².

A number of systems have been described specifically targeting gait rehabilitation using rhythmic pacing. One interesting example is "Walk-Mate"⁶³. This system simulates the spontaneous synchronization between two individuals walking together⁶⁴. The patient walks to an auditory rhythmic stimulus that mimics the sound of the footsteps of an actual person. The idea behind this Walk-Mate is that it might be easier for a patient to synchronize to a rhythm that is interactive and is constantly adjusted based on the patient's behaviour, as opposed to a fixed rhythm. It has been shown that the use of Walk-Mate improved the ability of patients to synchronize to the rhythmic stimulus compared to the use of a regular metronome⁶⁵, and improved walking symmetry and variation in foot contact time⁶⁶. Another interesting example is the ForceLink C-Mill, a treadmill combining auditory and visual cueing, used for gait- and obstacle avoiding training⁶⁷. The first results using C-Mill are promising—using this system a number of improvements on regular rehabilitation evaluation scales were found, including a 10-meter walking test and the Timed Up-and-Go test.

Although a number of methodologies using rhythmic pacing have been described, and in some instance are commercially available, a technology to accurately control overground speed does not yet exist. Given the previously discussed importance of overground speed, and the positive effects of rhythmic pacing in both exercise and

rehabilitation, I believe such a system would be very useful. In the next section I will discuss the physiological requirements for accurate control of overground speed using rhythmic pacing.

Physiological requirements for accurate speed control using rhythmic pacing

The ability to control overground locomotion speed by using rhythmic pacing depends, most of all, on the existence of a relationship between prescribed step frequency and preferred speed. If no such relationship exists, any attempt to control overground speed using rhythmic pacing would be fruitless. Fortunately, the existence of a relationship between prescribed frequency and speed has been demonstrated in both walking^{41,68} and running⁴⁰. Consequently, whenever the prescribed step frequency is changed, it can be expected that speed will change as well. Thus, the first requirement for controlling speed using rhythmic pacing is present.

The second requirement for accurate control of overground speed using rhythmic pacing is that changes in prescribed step frequency trigger fast responses in speed. For a speed control system to be useful, the actual speed of the user needs to accurately track the desired speed. Thus, if the desired speed changes, the actual speed would ideally also change quickly. Furthermore, the effect of any external perturbations that change the relationship between prescribed frequency and speed would be rejected rapidly. Such perturbations could be changes in ground surface, hills, wind, etc. If changes in prescribed frequency would only trigger slow responses in speed, it might simply take too long to respond to changes in the desired speed, or the effects of perturbations, for the system to be useful.

Although the dynamical response in speed following changes in prescribed step frequency is currently unknown, in recent locomotion studies my colleagues and I have found indication that a rapid process is present in the selection of preferred gait patterns. For example, during both walking and running, the majority of the step frequency adjustments following changes in prescribed speed occur within a few steps^{69,70}. A first indication that a similar fast mechanism might be present in the selection of preferred speed was recently provided by O'Connor & Donelan⁷¹, who showed that following a perturbation to visually perceived walking speed people rapidly changed their walking

speed to bring their visual speed back to their preferred speed. These findings show that a fast process is present in the selection of preferred gait patterns, at least in certain contexts (all mentioned studies were performed on a treadmill) and when certain perturbations are applied. It remains to be tested whether a similar fast process is present in the selection of preferred walking and running speed when the only constraint is to synchronize steps to a rhythmic stimulus. The main focus in Chapter 3 is to quantify the dynamics of the speed response following changes in prescribed step frequency. I believe that if indeed a strong, fast, relationship between prescribed step frequency and speed exists, rhythmic pacing could be employed to accurately control overground speed. Furthermore, a good understanding of these dynamics is essential when actually designing the control system.

Open-loop vs. closed-loop control of overground speed

To maximize the usefulness of an overground speed control system, ideally it would accurately control speed for a large number of individuals and in a wide range of conditions. The design of such a system would be very straightforward if an accurate model of the relationship between prescribed step frequency and speed could be acquired. This model could then be used to directly determine the required frequency to bring the user to their desired speed. Such a control system, where a predetermined signal is used for control, is typically referred to as an *open-loop* control system (figure 1.1A). If an accurate model of the frequency–speed relationship exists, using an open-loop control system would not only be the simplest method to control speed, it would actually be the preferred method as it avoids serious issues related to feedback based control methods⁷². However, if any uncertainty exists in the relationship between prescribed step frequency and speed this would lead to inaccuracies in controlled speed. Such uncertainties could be due to external perturbations, or complexities of the system(s) responsible for the frequency–speed relationship that are not captured in the model (i.e. *unmodeled dynamics*).

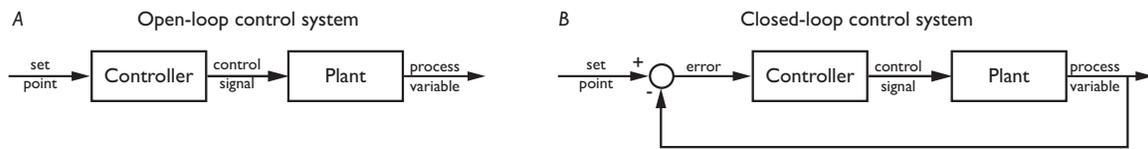


Figure 1.1 General control diagrams

The main purpose of any control system is to maintain the process variable as close as possible to the set-point. A) In an open-loop control system the control signal is determined based on a predetermined relationship between the control signal and the process variable. If a highly accurate model of the plant exists, open-loop control could result in well controlled behaviour. In the ideal case the controller would be the inverse of the plant—in this case the controller and plant would cancel each other out, and the process variable would be exactly equal to the set-point. Unfortunately, in practice a perfect understanding of the plant is usually impossible to achieve. One downside of an open-loop system is that any uncertainties in the plant would lead to differences between the process variable and the set-point. Furthermore, an open-loop system is unable to respond to any external perturbations that change process variable. B) In a closed-loop control system the control signal depends on the error between the set-point and the process variable. As long as an error exists, a well-designed controller would automatically change the control signal in an attempt to reduce the error to zero. As a result, even if the understanding of the plant is imperfect a closed-loop control system could lead to highly accurate control (e.g. no error during steady state). Also, whenever external perturbations change the process variable, a closed-loop controller can respond to these changes thereby reducing the effect of perturbations.

To accurately control overground speed using rhythmic pacing when uncertainties exist in the relationship between prescribed step frequency and speed, a *closed-loop* control system can be employed (figure 1.1B). The basic idea behind a closed-loop control system is that, instead of relying on a perfect understanding of the system under control, the actual behaviour of the system can be measured and the control signal can be adapted based on this measurement. Since a perfect understanding of the system under control is usually impossible to achieve, closed-loop control systems are widely used. A common example of such system is the *cruise control* system in cars. The cruise control is responsible for maintaining the car at the desired speed, and is thus directly comparable to what I am trying to achieve here. Whenever the system detects that the car's speed is different than the desired speed, the opening of the throttle is adjusted to change the car's speed towards the desired speed. After careful tuning, this guarantees that the car will stay at the desired speed, despite changes in the car (e.g. changes in mass due to passenger number or changes in fuel amount) and external perturbations such as hills. In contrast, in order to make an accurate *open-loop* cruise control system, all these potential factors affecting the relationship between throttle opening and car speed would have to be anticipated when designing the system. Clearly, using a closed-loop system is preferable whenever uncertainties are present. The accuracy limits of using an open-loop control system to control overground locomotion speed will be

determined in Chapter 3. The focus of Chapter 4 will be to develop and test a closed-loop system for accurately controlling overground locomotion speed.

Aims

The overall goal of this thesis is to explore the possibility of using rhythmic pacing to control overground speed during walking and running. A number of basic scientific questions will be addressed to determine the potential and viability of such speed control system, and to enable its development. The specific aim of Chapter 2 is to determine the performance improvement that can be expected from more accurate speed control during running. Towards this goal, my colleagues and I will determine how well recreational runners are able to control their own speed, and estimate how the resulting pacing inaccuracies impact optimal running performance. The specific aim of Chapter 3 is to determine the viability of using rhythmic pacing to accurately control overground walking and running speed. Towards this goal we will determine the dynamical response in walking and running speed following changes in prescribed step frequency, and determine the accuracy limits of an open-loop speed control system. The specific aim of Chapter 4 is to further improve the speed control accuracy over the accuracy of an open-loop control system. Towards this goal we will develop a closed-loop system for controlling overground speed, and test the performance of this system in both walking and running. And finally, the specific aim of Chapter 5 is to transfer the knowledge gained in this thesis to the general public. Towards this goal, we will translate the overground speed control system into a user-ready product.

Chapter 2. Effect of pacing error and variability on the optimal performance of recreational runners

Abstract

Previous research has shown that recreational runners are less well able to control their running speed compared to highly trained athletes. However, it is currently unclear how this reduced ability to control speed affects optimal running performance. The first goal of this study was to further quantify the ability of recreational runners to control their speed. Towards this goal, we first instructed participants to run 1600m at their preferred speed. We then asked them to repeat the run at speeds 10% above and 10% below their preferred speed. We quantified both the pacing error (defined as the difference between the target speed and participants' actual speed) and the pacing variability (defined as the speed fluctuations around the participants' average speed). We found that the absolute pacing error was $+3.9\pm 3.2\%$ on average. The pacing variability, quantified as the coefficient of variation, was $3.0\pm 1.4\%$. We used a simulation approach to estimate how the pacing error and pacing variability found here affects optimal running performance. Our simulation results suggest that the pacing error found here decreases running performance by roughly 5% on average for a 5 kilometer run. These results suggest that the running performance of recreational runners could be improved by enhancing their ability to achieve and maintain target speeds.

Introduction

Maximum running performance is more variable in recreational runners compared to highly trained athletes⁷³. That is, if an athlete would repeat the same race their final times would be tightly grouped, whereas the times of a recreational runner would show much higher variability. While it is possible that the performance of recreational runners is more variable because they are less motivated to perform optimally during each race⁷³, perhaps part of this increased variability is because recreational runners are actually unable to consistently reach their optimal performance. It has previously been

shown that recreational runners are less well able to run at specific target speeds compared to highly trained athletes⁵. This decreased ability to accurately control running speed could well result in a decreased ability to consistently reach optimal performance. However, to what extent such pacing inaccuracies actually influence optimal running performance is currently unknown. We believe that an improved understanding of the effect of pacing inaccuracies on performance is desirable, because it provides insight in the performance enhancements that could be expected from an increased ability to control running pace.

Perhaps the most important skill in controlling running pace is the ability to accurately achieve a target pace, as any steady-state offset in running pace is likely to compromise performance. When running faster than the optimal constant pace for a particular distance, early exhaustion is likely⁷⁴⁻⁷⁶. Following exhaustion the pace necessarily has to drop considerably⁷⁷, resulting in a decreased average pace over the entire run^{77,78}. When running slower than the optimal constant pace, time will be lost that might be impossible to be regained during the remainder of the run⁷⁸, again leading to a decrease in performance. As far as we are aware, only one study has looked into the ability of recreational runners to accurately control their running speed⁵—one goal of the current study was to determine if we could reproduce the previously found results.

A second important skill in controlling running pace is the ability to maintain pace constant. Although it has been demonstrated that it is possible to match the optimal constant-paced performance in endurance activities while varying pace⁷⁹⁻⁸¹, modeling work by Fukuba & Whipp⁷⁸ suggest that it is not possible to beat this performance. Thus, maintaining speed constant throughout the run is theoretically optimal, limited variability in speed will not necessarily decrease performance, but too much variability will. The work by Fukuba & Whipp also suggested that the amount of variability in speed allowed before reducing performance decreases with increasing event duration. Indeed, it is generally believed that maintaining an even pace is more important during longer events^{3,4,76}. This is supported by the finding that during the current men's world records the coefficient of variation in *within-race* running speed continuously decreases from 4.5% in the 800-meter event to 1.5% in the 10000-meter event⁸². As far as we are aware, the ability of recreational runners to maintain a constant pace is currently unknown.

We had two main goals with this study, with the first focused on quantifying the ability of recreational runners to achieve specific target paces and maintain their pace constant at these target paces, and the second focused on estimating the effects of pacing inaccuracies on optimal running performance. Towards the first goal, we instructed subjects to run at specific speeds and measured how well they were able to do so. Towards the second goal, we used a simulation approach to estimate the consequences of the pacing inaccuracies found here on optimal running performance. The advantage of using a simulation approach was that the effect of pacing error and variability could be determined independently, and that a range of difference scenarios could be tested (e.g. events of different length). The mathematical model used in our simulations was inspired by Fukuba & Whipp's modeling work when studying the effect of pacing strategy on optimal performance⁷⁸.

Methods

Experiment

Fourteen naïve, healthy volunteers participated in this experiment (13 men, 1 women; age 29 ± 7.6 years; height 1.78 ± 0.63 m; body mass: 72.9 ± 8.7 kg; means \pm SD). All subjects were recreational runners, running between 2 and 5 times per week. Before the single-day experiment, subjects were familiarized with the equipment during a 10-minute warming up over a range of self-selected running speeds. The experiment was performed on a standard 400-meter athletics track⁸³. The Simon Fraser University's Office of Research Ethics approved the protocol, and participants gave their written informed consent prior to the experiment.

Experimental setup

We used a GPS-based speed sensor designed for high-accuracy speed sensing to measure instantaneous running speed (VBOX Speed Sensor, Racelogic, UK). Speed data was logged at 10Hz using an Arduino Uno microcontroller. The GPS and Arduino were mounted onto the frame of a lightweight backpack that was worn by the subject during the experiment (total mass: 1.5kg, figure 2.1).



Figure 2.1 Experimental setup

We measured speed using an accurate GPS-based speed sensor, and data was logged using a microcontroller. All equipment was mounted to a lightweight backpack frame carried by the participants. Note that the headphones were only used in the experiments described in Chapters 3 and 4.

Prior to the experiment, we verified the accuracy of the speed sensor by determining the average and instantaneous speed error. To determine the average error, we walked and ran a known distance at various speeds and compared the integrated speed measurement to the actual distance. The resulting average speed error was $0.2 \pm 0.4\%$ (mean \pm SD). To determine the instantaneous error in speed measurement, we mounted the speed sensor to a cart instrumented with an optical encoder that allowed for precise speed measurement. We then pushed this cart around the track while walking and running at various speeds. We applied a one hertz Butterworth filter to both the GPS and encoder data to reduce within-stride speed variations. After shifting the GPS data by the measurement delay (0.16 ± 0.08 s, determined from the peak in the cross-correlation between the GPS and optical encoder data), the root-mean-square-error between the GPS and encoder data was $0.8 \pm 0.5\%$ (mean \pm SD). These results show that the speed sensor indeed accurately measured both the average and instantaneous speed.

Experimental protocol

Each participant performed three 1600-meter trials. Before each trial we instructed the participants to keep their pace as constant as possible, and to stay in the running track's inside lane. We asked subjects to remove their watch for the duration of the experiment.

The goal of the first trial, named *preferred* trial, was to get a baseline for the remainder of the experiment. During this trial participants were free to select their running pace. To prevent participants from running too fast in the preferred trial, resulting in an inability to complete the rest of the protocol, we suggested participants to aim for a comfortable 10-km pace. We also told them that they would have to be able to repeat the run at considerably higher and lower paces.

In order to quantify how accurately participants were able to achieve specific target speeds, each participant then performed two trials where we instructed them to either run 10% faster or 10% slower than their average speed in the preferred trial. Besides this relative pacing target, we also told participants their target speed and lap time in absolute terms. Basically, we aimed to provide participants with as much information as possible to help them achieve the target paces. The order of the *fast* and *slow* trial was randomized between subjects. Prior to each trial, we reminded participants of their average speed and lap time during the preferred trial, and told them the target speed and lap time for the current trial. While participants were running, we reminded them of their target lap time after each completed lap, and the remaining number of laps for that trial.

In order to quantify participant's belief of how accurate they were able to pace their run, we asked participants to indicate their estimated pacing error for both the *fast* and *slow* trial by marking their estimated error on a continuous line (Appendix A). This was done after completion of the entire experiment to minimize the chance that participants would change their pacing strategy during the experiment.

To test whether the reported pacing errors were due to participants' inability to run at certain target speeds, following each trial participants rated their perceived exertion on a Borg scale⁸⁴. The maximum reported perceived exertion was well below maximal exertion, suggesting that this was not an issue.

Data processing & statistics

Besides typical noise involved with GPS measurements, an additional source of noise in our speed measurements was that the GPS sampling rate was only 10-Hz. As a result, the within-stride speed fluctuations were not well captured, and the location within each stride where speed was measured varied with step frequency. When not filtering

adequately, this results in speed changes due solely to changes in step frequency. To avoid influence of within-stride speed variability and measurement noise on the estimated pacing variability we first filtered all data using a five-seconds moving average filter.

We quantified the pacing error as the difference between the target speed and the average actual speed during the *fast* and *slow* trials (figure 2.2). We determined the pacing variability as the speed variation around the average actual speed (figure 2.2). To quantify the pacing variability we first calculated the root-mean-square-error between the actual speed and the average actual speed, and then divided this by the average actual speed to obtain the coefficient of variation.

We used non-parametric statistical tests to test for significant differences. Due to the relatively small sample sizes used in the experiments, it was not possible to confirm that the population data of the parameters of interest were normally distributed. We used Wilcoxon signed-rank test⁸⁵ for paired-sample tests, and Wilcoxon rank-sum test⁸⁵ for individual-sample tests. We calculated Pearson's correlation coefficient⁸⁵ to determine if a relationship existed between how well participants believed they performed and how well they actually performed. To determine whether differences existed between average running pace in different laps, and whether difference existed between the pacing variability in different laps, we used Friedman's test (non-parametric equivalent of a repeated measures ANOVA) followed by a Bonferroni post-hoc analysis⁸⁵. All statistical testing was performed using Matlab (Mathworks, Natick, MA). We considered a probability less than 0.05 as significant. All reported results are mean±standard deviation.

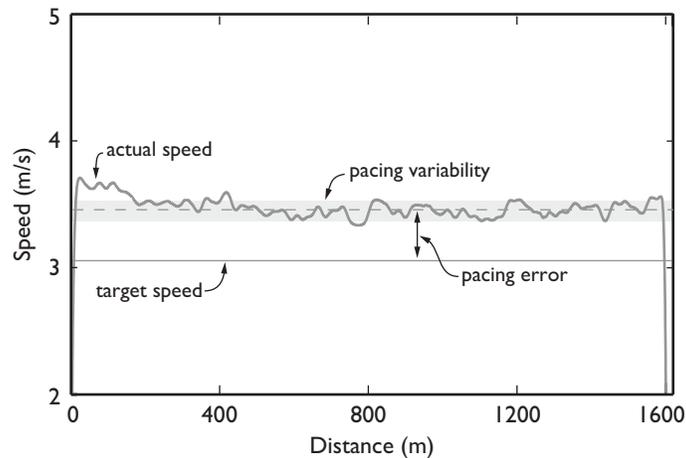


Figure 2.2 Pacing error and variability definitions

We determined the pacing error as the difference between the target speed and the average actual speed (dashed line). We determined pacing variability as the variability in actual speed around the average actual speed.

Simulations

We performed Monte-Carlo simulations to estimate how the pacing error and variability found in this study affect optimal running performance. The basic idea in Monte-Carlo simulations is to perform repeated simulations of a mathematical model describing the process of interest, while varying some of the model parameters based on their assumed probability distributions between simulations⁸⁶. The repeated simulations then result in a predicted effect of the variations in these parameters on the final outcome. Here, the process of interest is a runner trying to cover a specific distance in the least time possible, and the outcome of interest is the effect of pacing error and variability on final running time (and thus on average speed).

The mathematical model used in our simulations is the relationship between workout intensity and maximally sustainable duration. It is well known that the maximal duration for endurance activities decreases with increased power (cycling) or speed (running and swimming). A hyperbolic relationship using two parameters has been shown to accurately describe this relationship for a range of activities and fitness levels^{74,77,82,87-95} (figure 2.3). The first parameter is the asymptote of the speed-duration curve when time goes to infinity. This asymptote is believed to depend on aerobic capacity⁹⁶⁻⁹⁸. Dependent on the mode of exercise, this asymptote is referred to as the *critical speed* or *critical power*. The second parameter is the relationship's curvature, and is believed to reflect anaerobic capacity⁹⁴. The curvature is mathematically equivalent to a fixed

amount of work or distance that can be performed at intensities above the critical speed/power, and is commonly referred to as the *anaerobic capacity*.

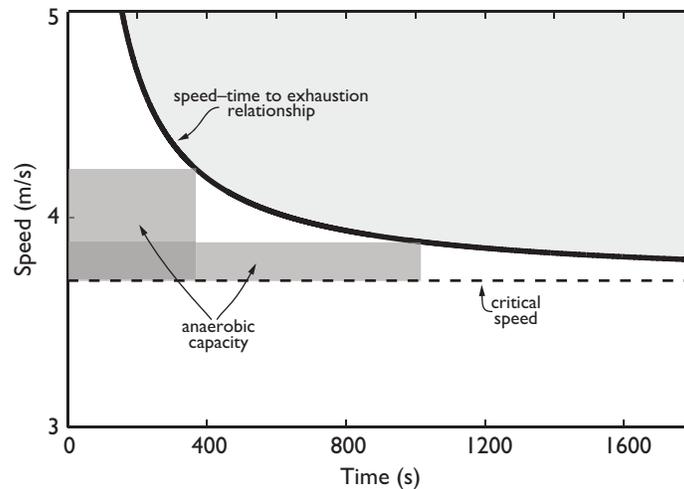


Figure 2.3 Relationship between running speed and time to exhaustion

Time to exhaustion decreases with increased running speed. It has been shown that this relationship is well characterized by two parameters. The first parameter is the asymptote as time goes to infinity. This critical speed is believed to depend on the aerobic capacity, as it represents the maximum speed that—in theory—could be maintained indefinitely. The second parameter is the curvature of the relationship. This curvature is mathematically equivalent to a fixed amount of distance that can be covered using speeds above the critical speed. This distance is believed to depend on the amount of anaerobic energy available, and is referred to as the anaerobic capacity. The area of the two gray rectangles is the same, illustrating the equivalence between the curve of the relationship and a fixed distance (area = time x speed = distance).

To determine the effect of the pacing error and variability on optimal running performance we performed 1000 simulations of a five-kilometer run. We used a distance of five kilometer as this is by far the most popular race distance for recreational runners in North America⁹⁹. During the simulations we used the average values for the critical speed (3.7m/s) and anaerobic capacity (200m) reported by Pepper⁹⁰. These values were determined in moderately fit males, so can be expected to be a good approximation for the average recreational runner. In each simulated run the target pace was the optimal constant pace. We determined the performance effects of pacing error and pacing variability separately, by either adding an offset or variability to the target pace. We also tested the combined effect of pacing error and pacing variability. Each simulation was terminated when the runner reached the five-kilometer point. If the runner exhausted the anaerobic capacity prior to reaching five kilometer, speed was reduced to 90% of the critical speed for the remainder of that simulation. Note that this 90% is an assumption based on the experimental finding that speed had to drop below the critical speed to

continue exercise following exhaustion⁷⁷. Because the simulation results depend on the choice of this value, we will return to this assumption in the discussion.

Since the distribution of the performance reduction due to pacing inaccuracies was generally not normally distributed, we used the non-parametric Wilcoxon rank-sum test to test for significant differences between the predicted optimal performance and the performance when pacing error and/or variability was added⁸⁵.

Results

Experiment

On average participants ran 3.27 ± 0.32 m/s in the preferred trial, 2.99 ± 0.28 m/s in the *slow* trial, and 3.70 ± 0.35 m/s in the *fast* trial. Example time-series data for two subjects are shown in figure 2.4.

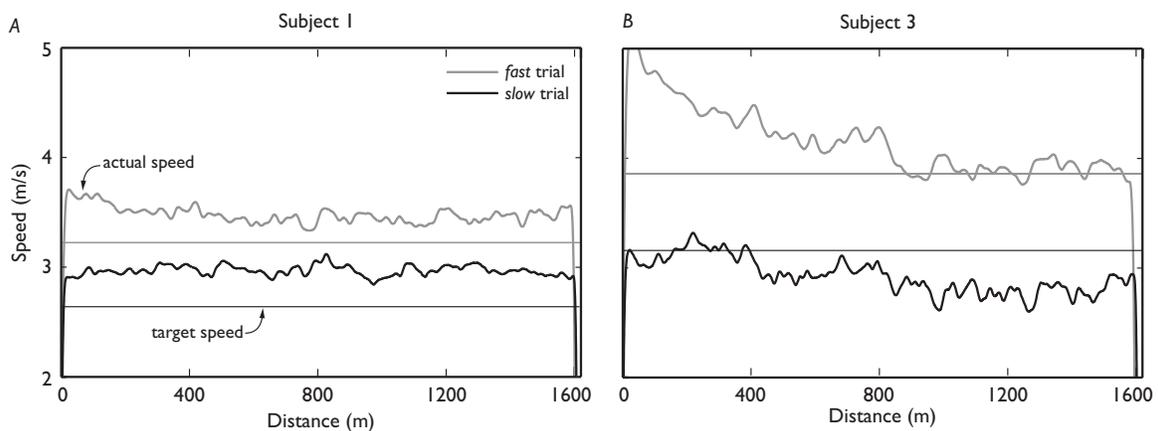


Figure 2.4 Example time-series data

Example data for two subjects during the fast and slow trial. A) Example data for a subject with relatively high pacing error but relatively low pacing variability (as compared to other participants). B) Example data for a subject with both relatively high pacing error and relatively high pacing variability.

The average error between the target speed and actual speed, across the *fast* and *slow* trial was $+2.3 \pm 4.6\%$. Participants on average ran too fast in the *fast* trial ($+2.9 \pm 3.1\%$, range: -3.8 – 7.0% , $p=0.01$, figure 2.5A). In the *slow* trial they ran slightly too fast as well ($+1.8 \pm 5.8\%$, range: -8.2 – 11.7% , figure 2.5A), although this was not significantly different from zero ($p=0.09$). However, when asked to estimate their pacing error, participants reported that they believed they ran too fast in the *fast* trial ($+6.8 \pm 6.0\%$, $p=0.01$) and too slow in the *slow* trial ($-4.4 \pm 6.9\%$, $p=0.09$, figure 2.5B). The actual performance was

significantly different from how well participant's believed they performed (*fast*: $p=0.01$, *slow*: $p=0.01$). Furthermore, we found no relationship between how well participants performed and how well they believed they performed (*fast* trial: $R=0.44$, $p=0.11$, *slow* trial: $R=0.17$, $p=0.55$, figure 2.5C). For example, one participant who estimated that he ran 10% slower than his *slow* target speed, in reality ran 11% too fast.

When disregarding the direction of the pacing error to determine participants' absolute deviation away from the target speed, the average pacing error across all participants and both trials was $3.9\pm 3.2\%$. The average pacing error across all participants was $3.5\pm 2.4\%$ in the *fast* trial and $4.5\pm 4.0\%$ in the *slow* trial. Participants believed that they performed significantly worse in both trials—their estimated absolute deviation was $7.1\pm 5.6\%$ ($p=0.02$) and $7.3\pm 3.4\%$ ($p=0.04$) in the *fast* and *slow* trial, respectively.

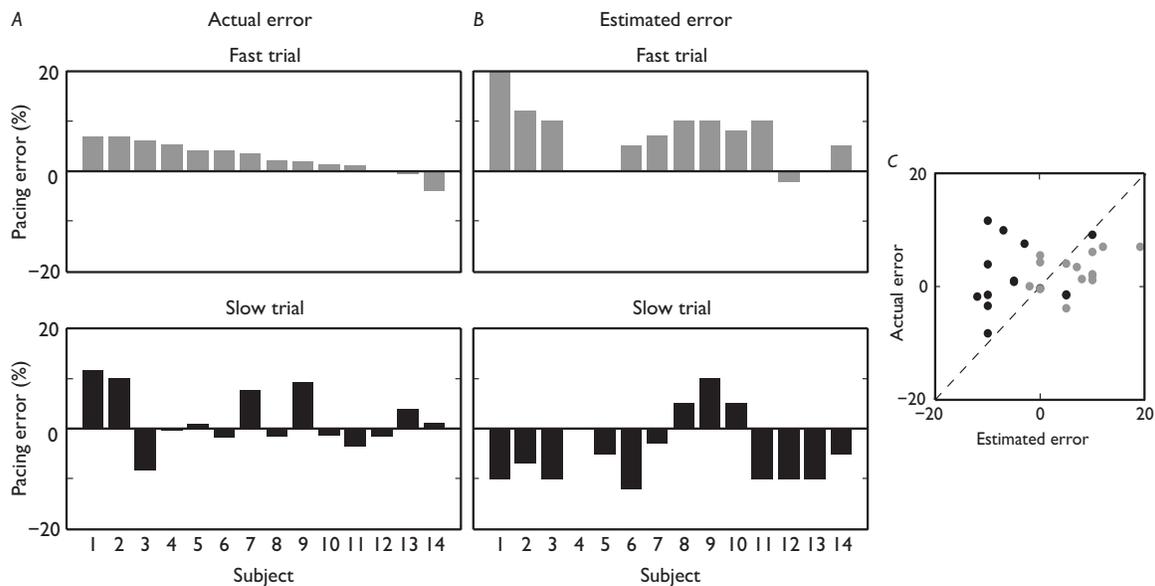


Figure 2.5 Pacing error results

Pacing error results during the fast and slow trials. A) Actual error between the target speed and actual speed for each subject. B) Estimated error between the target speed and actual speed for each subject. This estimated error was obtained using a questionnaire asking how much difference participants believed existed between the target speed and their actual speed. C) Relationship between the actual and estimated error. If participants had a good idea of their pacing accuracy, the data would have been close to the dotted line. This is not the case, suggesting that participants had a poor idea of their ability to pace themselves.

The average variability in instantaneous running speed across all subjects, quantified as the coefficient of variation, was $3.0\pm 1.4\%$. Part of this variability was because the first lap was covered significantly faster than the remaining laps ($+3.6\%$, $p=2.0\times 10^{-7}$), where the average speed remained constant. Variability in lap times, quantified as the coefficient of

variation, was $2.3 \pm 1.7\%$. This variation decreased to $1.6 \pm 1.2\%$ when we disregarded the first lap for each subject. We did not find any difference in pacing variability between the *preferred*, *fast* and *slow* trials ($p=0.93$).

Simulations

The pacing error and pacing variability used in each simulation were randomly selected from the empirical distributions found in our experiment. The pacing error distribution used in the simulations was the distribution of pacing errors across the *fast* and *slow* trials. Because the pacing error distribution across the *fast* and *slow* trial was not different from a normal distribution ($p=0.96$, Kolmogorov-Smirnov test), for each simulated run the pacing error was randomly selected from a normal distribution with an average of 2.3% and a standard deviation of 4.6%. Since the distribution of the pacing variability was skewed to the right (figure 2.6A), this was not approximated well by a normal distribution. To model the pacing variability distribution, we performed a logarithmic transformation on the pacing variability data so that the distribution was closer to normal¹⁰⁰($p=0.80$, Kolmogorov-Smirnov test). During each simulation, we randomly selected a value from this transformed distribution. We then used the inverse transformation to get the actual variability to be used in the simulation. As shown in figure 2.6, this procedure indeed resulted in a better approximation of the pacing variability distribution compared to assuming normally distributed data.

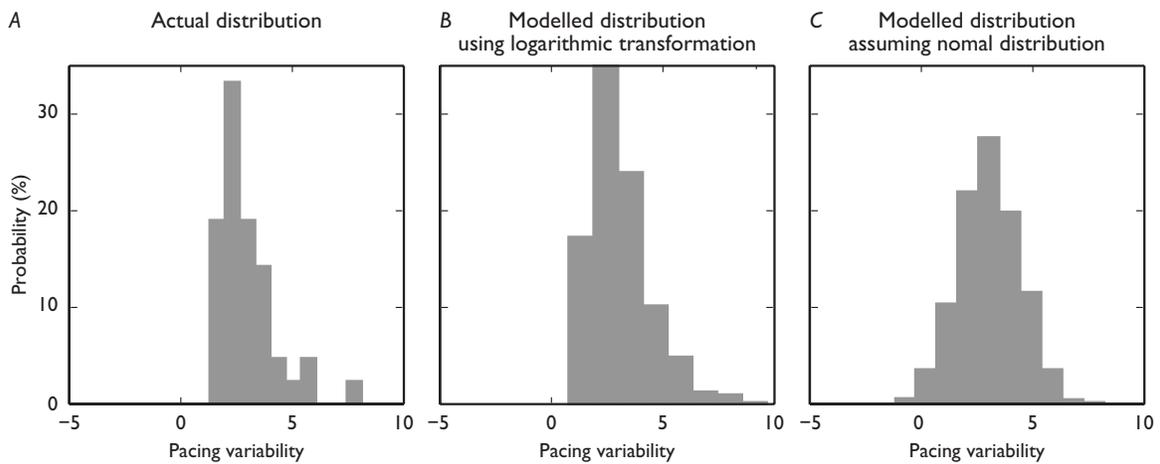


Figure 2.6 Modeling of the pacing variability distribution

A) Actual measured pacing variability distribution during the experiment across all participants. B) Model of pacing variability distribution used during simulation. This distribution was obtained by first applying a logarithmic transformation to the distribution in A, to make it closer to normal. We then randomly selected 1000 values from a normal distribution with mean and standard deviation equal to this transformed distribution. The inverse of the logarithmic transformation was applied to these 1000 values to determine the pacing variability. The distribution of the resulting pacing variability's is shown. C) Model of the pacing variability if we had assumed that pacing variability is normally distributed. Although the mean and standard deviation in both B and C are equal to the mean and standard deviation in A, it is clear that the distribution in B better describes the actual distribution in A.

Example results of the Monte Carlo simulations are shown in figure 2.7. The pacing error found in our experiment resulted in an average decrease in performance of $4.6 \pm 2.5\%$ for a 5-kilometer run (figure 2.8A, $p=0.00$). This equates to an average time loss of one minute for our simulated runner compared to its theoretical optimal performance of 21.6 minutes.

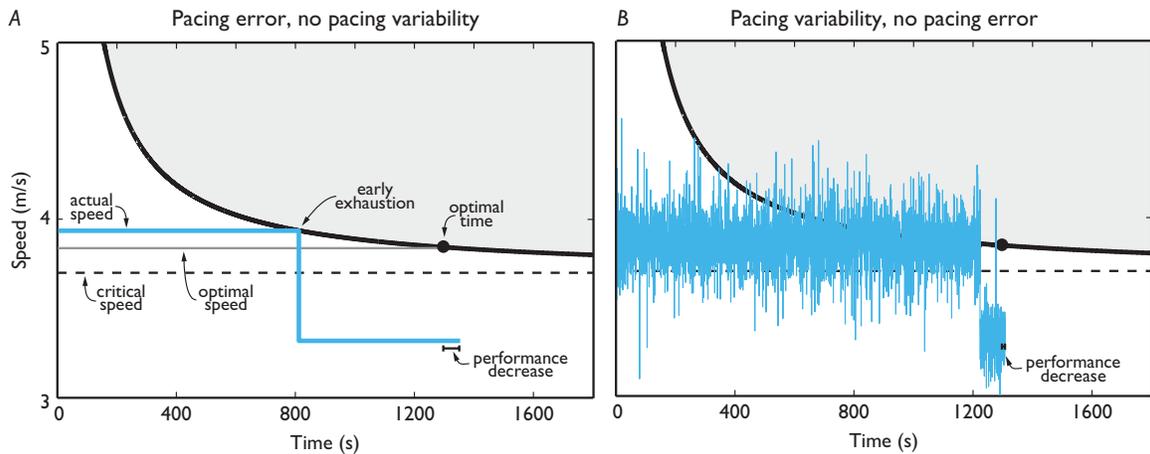


Figure 2.7 Example results of Monte Carlo simulations

A) Simulated effect of pacing error on the time to cover 5000-meter. In this case the pacing error resulted in the 'runner' starting too fast (actual speed initially above optimal speed). As this speed can only be maintained for ~800 seconds, the runner is exhausted at this point. Following exhaustion, speed has to drop considerably. The effect of covering part of the run faster than the optimal speed, and another part of the run slower, is a decrease in performance. B) Simulated effect of pacing variability on the time to cover 5000-meter. Here, the pacing variability results in the 'runner' being exhausted just prior to the end of the run, again leading to a reduced speed for the remainder of the run.

The pacing variability found in this study had considerably less effect on the simulated optimal performance. The average decrease in performance due to pacing variability was $0.7 \pm 0.1\%$ (figure 2.8B, $p=0.00$). This equates to an average time loss of 10 seconds compared to the optimal performance for our simulated runner.

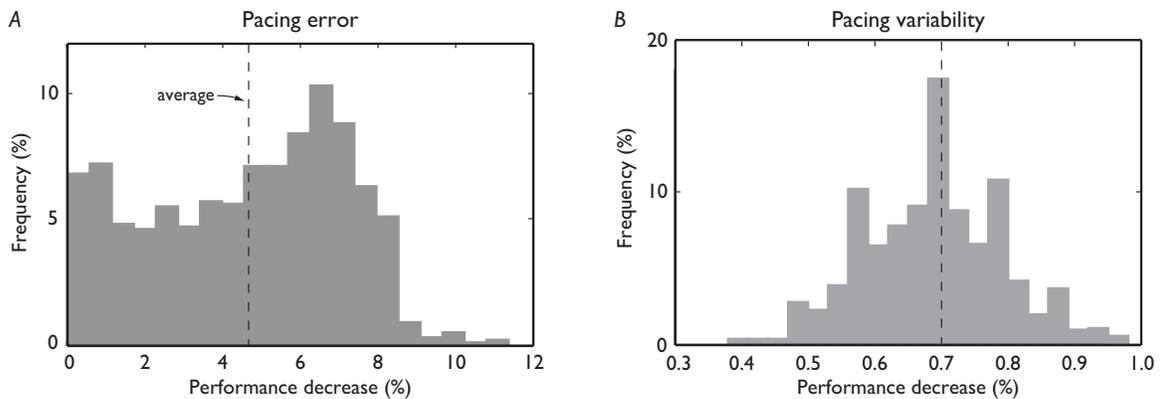


Figure 2.8 Monte-Carlo simulation results

A) Distribution of performance decrease as a result of pacing error. The average decrease in performance due to pacing error was 4.6%. B) Distribution of decrease in performance as a result of pacing variability (average 0.7%). Clearly, pacing error has a considerably larger effect on performance than pacing variability.

The effect of pacing error and variability combined was $4.7 \pm 2.5\%$ ($p=0.00$). This was not significantly different from the effect of pacing error alone ($p=0.15$).

Discussion

The pacing error found here was considerably smaller than previously reported results. In a study on the difference in pacing ability between recreational runners and collegiate athletes⁵, it was found that recreational runners made an average pacing error of 9.5 ± 6.6 seconds per 400-meter lap. In contrast, the pacing error found here equates to an error of 5.2 ± 4.2 seconds per lap. Although the most obvious explanation for this difference would be that participants in our study were more experienced runners, we will discuss a number of other possibilities that we think might underlie this difference. First, we believe that the instructions given to participants might explain part of this difference. In the *fast* and *slow* trials we instructed participant's to run 10% faster or slower than their average preferred speed in the *preferred* trial. We also told participants their target speed and lap time. In contrast, participants in Green's study were only given the target lap times, to mimic the situation where a coach instructs the athlete. If it is easier for recreational runner's to make relative adjustments to their pace as opposed to targeting absolute paces, the difference in pacing error might be due to the difference in instructions. Second, the difference between the results might be caused by a difference in the speeds used. We instructed participants to run at a comfortable 10-kilometer pace in the *preferred* trial. This was then used as the reference pace in the other trials, were participants were instructed to run 10% faster or slower. The reference pace in Green's study was selected as the average pace during a maximal 3200-meter run. Participants were then instructed to run 7% faster or slower in consequent trials. As a consequence, the reference speeds were higher (range: 3.1–4.8 m/s) in the study by Green than the reference speeds used in this study (range: 2.7–3.8 m/s). If pacing accuracy indeed decreases with increased speed, the effect of pacing error on optimal performance might be larger than estimated here. We propose that future studies are needed to gain more insight into the factors affecting pacing ability, including instructions and running speed.

Our simulation results suggest that the pacing inaccuracies made by recreational runners decreases their optimal performance. The results further demonstrate that the inaccuracy in achieving a target pace (*pacing error*) is more likely to reduce performance than the variability in running pacing around the target pace (*pacing variability*). In fact,

the performance decreasing effect of pacing error and pacing variability combined did not increase over the effect of pacing error alone.

The presented theoretical average decrease in optimal performance due to pacing error is for a population of recreational runners—the actual decrease in performance might vary strongly between runners. Some recreational runners might be able to consistently achieve their optimal performance. But, for some runners the decrease in performance would be as large as 10%. In the latest Susan G. Komen race¹⁰¹, one of the largest 5-kilometer runs in North America, this performance decrease would have made the difference between finishing within the top 10% or well outside the top 20% (a difference of almost 300 places in the ranking). The average performance decrease predicted from our simulations would have made the difference between finishing within the top 10% or just outside the top 15% (over 100 places difference in the ranking). Clearly, the improvements that can be gained from an enhanced ability to achieve desired running speeds could, at least in theory, make a real difference for individual runners.

Our simulation results suggest that the pacing inaccuracies made by recreational runners might explain part of the variability in maximal performance of recreational runners. In a study by Nicholson and Sleivert¹⁰², including both recreational and competitive runners, it was found that the coefficient of variation between two experimental 10-kilometer time trials was 3.7%. This is similar to the performance variability found in the slower half of male athletes during actual summer road races—the coefficient of variation was 3.9% on average for these runners⁷³. In contrast, the performance variability in the faster male athletes was only 1.6% on average. The author's proposed explanation for this difference was a difference in competitive experience and motivation level. Here we found that the theoretical variability in performance due to pacing error, quantified as the coefficient of variation, was 2.4%. This suggests that at least part of the increased variability in maximal performance in less experienced runners might, at least in theory, be explained by a decreased ability to accurately achieve their desired pace.

We believe that our main simulation results are still valid even if the relationship between running speed and time to exhaustion would differ from the theoretical model we used in our simulations. Although the exact influence of pacing error on performance would be different, it is unlikely that the existing pacing error in recreational runners would not

have a considerable effect. There are two factors that our findings rely upon. The first assumption is that there is a physiological system that can provide the energy required to continue exercising regardless of workout intensity, up till some maximal intensity (i.e. the critical speed). The aerobic energetic system has this ability¹⁰³. The second assumption is that there is a limited storage of 'extra' energy that can be used to temporarily increase exercise intensity above the critical speed. Indeed, the contribution of the anaerobic energy system has been found to be independent of exercise duration, especially during prolonged exercise¹⁰³. Regardless of the actual relationship between workout intensity and time to exhaustion, especially in exercise of prolonged duration there will be a fine line between going too slow and going too fast. When going too slow, the aerobic system is not utilized to its maximum, and there is not enough anaerobic capacity to make up for this lost time later. When going too fast, the risk of depleting the anaerobic capacity too early increases, resulting in an increased change of early exhaustion.

We believe that our main simulation results are still valid even if differences exist between the pacing strategy employed during our simulation—maintain a constant pace until exhaustion—and a typical pacing strategy used during races⁷⁵. Although a different pacing strategy would change the exact influence of pacing error on optimal performance, it is unlikely that this will invalidate our main findings. In fact, any deliberate pace changes during an exhaustive run can be expected to increase the negative effect of pacing error on performance. A higher than optimal pace during some part of the race requires that some other part of the race is covered slower than optimal to avoid early exhaustion. As a result, during this slower part of the run, the likelihood increases that the speed will drop below the critical speed as a consequence of pacing error, thereby increasing the chance of losing time that cannot be recovered.

One factor that does significantly influence our simulation results is the workout intensity achievable following exhaustion. The value we used in our simulation was based on the finding by Coats and colleagues that following exhaustion cyclists could maintain 90% of the critical speed for just over 10 minutes on average⁷⁷. However, the resolution used in the study by Coats was fairly low—they tested the duration of exercise that could be performed following exhaustion at 80, 90 and 110% of the critical power. On average subjects were able to maintain 110% of the critical power for only 30-seconds. However,

it is currently unknown for what duration exercise could be continued at intensities between 90 and 110%. To get an idea of the sensitivity of our simulation results to the choice of this parameter, we repeated the simulation using a value of 95% of the critical speed. This reduced the time lost due to pacing error by just over 40%, or 24 seconds ($p=7.4 \times 10^{-67}$). Clearly, the choice of this value has a significant effect on the results presented here.

Based on our findings that recreational runners generally tend to run too fast, the optimal pacing strategy for these runners might actually be to target a slightly lower pace than theoretically optimal. Due to the bias between actual and perceived speed, targeting a lower speed would result in an increased likelihood that the runner actually hits their optimal speed. Indeed, when using such a *conservative approach* in our simulation the time lost due to pacing error decreased by almost 10%, or six seconds ($p=1.1 \times 10^{-8}$). This result was achieved by correcting the target pace by the average pacing error, so that on average the simulated pace equalled the optimal pace.

The effect of pacing error on optimal running performance would be different for runners of different fitness levels, even if they have the same absolute pacing error. Increases in either the anaerobic capacity or the critical speed will lead to a decreased effect of pacing error on performance. To get insight in the expected range of this effect, we repeated our simulation using the lowest and highest fitness level reported by Pepper⁹⁰, by adjusting the anaerobic capacity and critical speed used in the simulation. The expected decrease in performance ranged from $4.0 \pm 2.2\%$ for the fittest individual to $5.8 \pm 3.0\%$ for the least fit individual. This suggests that the performance decreasing effect of pacing inaccuracy is relevant for a large range of individuals.

The effect of pacing error on optimal running performance would also be different for events of different duration. To get insight into this effect, we repeated our simulations for distances ranging from 1000-meter to 10-kilometer. The expected decrease in performance ranged from 2.3% for a 1000-meter run to 5.8% for a 10-kilometer run. This increased effect for events of longer durations is explained by the smaller difference between the critical and the optimal speed for longer distances. As a result, the chance of the speed dropping below the critical speed increases with increasing distance.

Our simulation results suggest that recreational runners could improve their optimal performance by improving their pacing accuracy. This improvement could either come from training, or from using currently available speed sensing technologies to monitor running speed such as GPS-watches or stride sensors. Finally, novel technologies could be developed to help (recreational) runners pace themselves. One interesting possibility would be to pace runners by prescribing their running cadence using for example a metronome. It has previously been shown that a clear relationship exists between prescribed cadence and self-selected running speed⁴⁰. Since people often spontaneously synchronize their movements to rhythmic stimuli^{23,24}, this might be a way to help runners pace themselves without requiring much attention. We will determine the viability of such running speed control system in Chapters 3 and 4.

Our study had a number of important limitations. First, our participants were predominantly males. Although there is no a priori reason to expect a sex-based difference in pacing ability, it would be preferable to confirm our findings in a population including more females. Second, in retrospect it might have been better to separate the instruction to meet certain target paces, and the instruction to maintain a constant pace, into separate trials. In the current approach, if participants believed they were not hitting the target pace, they could change their pace to better match the target but at the cost of increasing their pace variability. Third, to better reflect a typical running situation, it might have been better to instruct subjects to change their pace within the same run (e.g. “please run two laps at your preferred pace, followed by two laps at a 10% higher/lower pace”). This way the delay between the preferred and paced runs would be removed, perhaps increasing pacing accuracy. Fourth, it would have been preferable to use higher running speeds in our experiment—if indeed pacing error is dependent on speed, this would have better reflected recreational runners’ pacing inaccuracy during exhaustive running. For future studies on pacing accuracy we recommend utilizing a range of target speeds to determine whether runners’ pacing inaccuracy depends on the absolute running speed, and/or on the magnitude of the difference between runners’ preferred speed and a target speed. Finally, including elite runners in our experiment would have improved the generalizability of our findings.

In conclusion, we found that the pacing inaccuracy made by recreational runners has the potential to considerably decrease their optimal running performance. This suggests that

it is worthwhile for recreational runners—especially those who are interested in reaching their optimal performance—to spend time practicing the ability to accurately achieve target paces, or to invest in devices that can help them achieve their desired pace.

Chapter 3. Dynamic response in walking and running speed following changes in prescribed step frequency

Abstract

We have previously suggested that improved control of walking and running speed could be useful in both rehabilitation and exercise. The goal of this chapter was to determine the viability of using auditory rhythmic pacing to control overground walking and running speed. Towards this goal, we first determined the variability in the steady-state relationship between prescribed step-frequency and speed, both within and between participants. The result of this experiment provides insight into the accuracy that can be expected from a speed control system that relies on a predetermined relationship between prescribed frequency and speed (*open-loop speed control system*). We found that the use of such an open-loop speed control system results in a pacing error of $2.7 \pm 3.0\%$ in walking, and $3.7 \pm 3.2\%$ in running. As we have previously shown that recreational runners make a roughly 4% error when asked to run at a specific target speed, these results suggest that an open-loop system is unlikely to increase the speed control accuracy over people's own ability to control their speed. Because we expect that the speed control accuracy can be improved using a closed-loop speed control system—which would make the prescribed frequency dependent on the error between the target and actual speed—we also determined the dynamic response in walking and running speed following a change in prescribed step frequency. Knowledge of the dynamic speed response can aid in future development of such a closed-loop system. In both the walking and running experiment subjects responded to step frequency perturbations by first rapidly changing their speed towards their preferred speed, and then slowly fine-tuning their speed to converge onto their preferred speed. We measured similar response times for the fast process in walking ($1.7 \pm 0.3\text{s}$) and running ($1.9 \pm 0.8\text{s}$). We also found similar response times for the slow process (walking: $26.7 \pm 5.8\text{s}$, running: $30.5 \pm 6.4\text{s}$). Finally, we found that the fast process, while quite variable in amplitude,

dominated the speed adjustments. The results of this study suggest that it might indeed be possible to use auditory rhythmic pacing to accurately control overground walking and running speed, but that a closed-loop speed control system would be required to do so.

Introduction

Strong relationships have been found between various gait parameters during steady state locomotion. For example, people walk at slow speeds and run at high speeds^{104,105}. And, they use lower step frequencies when moving slowly compared to moving faster^{40,41,68,106,107}. Once such relationship is known, it is in theory possible to ‘control’ a particular gait parameter by constraining a second parameter. For example, by prescribing the appropriate treadmill speed, step frequency could be maintained at the desired level. Here we are interested in the possibility of accurately controlling overground walking and running speed by prescribing step frequency using rhythmic pacing (e.g. by using a metronome). If this would indeed be possible, such overground speed control system might prove useful in exercise and rehabilitation (Chapter 1).

A good model of people’s behaviour when synchronizing steps to an auditory stimulus is important when designing a system that accurately controls speed. This model can be separated into two parts. The first part captures the steady-state relationship between frequency and speed. It is known that such relationship exists in both walking and running^{40,68,108}. However, a good understanding of the variability in this relationship, both within and between individuals, is important also. The required structure of a system to accurately control overground speed strongly depends on this variability. If little variability exists in the frequency-speed relationship within individuals, controlling overground speed could be as simple as prescribing the appropriate step frequency. Such control system is commonly referred to as an *open-loop* control system (figure 1.1A). Whether the same system, without any adjustments, could be used for different individuals would depend on the amount of variability between individuals. If significant variability exists between individuals the system would require calibration to ensure accurate performance. However, if considerable unexplained variability exists within each individual’s relationship, open-loop control would not be accurate. Note that such variability would not only include random variations in speed for a particular frequency due to small changes in the state of the individual. It would also include variations due to

external perturbations such as changes in ground surface¹⁰⁹, hills¹¹⁰, etc. In order for an open-loop system to accurately control speed in a large range of conditions, any external perturbation that significantly affects the frequency-speed relationship would need to be accounted for. For example, if ground surface would indeed change the relationship between frequency and speed, the model would need a term to capture this effect. If indeed significant variability exists in each individual's frequency-speed relationship, a *closed-loop* control system could be used instead to reduce the effects of this variability (figure 1.1B). Instead of using a predetermined step frequency to drive the user to the desired speed, such system continuously adjusts the prescribed frequency based on the difference between the desired speed and the actual speed of the user. Since the prescribed frequency is directly related to the actual speed of the user, this system is able to respond to changes in the relationship between frequency and speed. For example, instead of detecting that the ground surface changed and predicting the effect of this new ground surface, the system would simply detect that speed changed, and adjust the prescribed frequency accordingly.

The second part of the model captures the dynamics of the speed changes following changes in prescribed step frequency. Accurate knowledge of these dynamics is especially important when designing a closed-loop control system. As the control system is placed in a loop with the person (figure 1.1B), the controlled behaviour (i.e. the behaviour of the person once the controller is added) will be dependent on the interaction between person and control system. If the control system is not properly designed, undesirable effects can occur such as oscillations and instability⁷². Having access to a dynamic model of the person allows for a structured approach to designing the control system, as opposed to a trial-and-error approach. For example, by using a dynamic model the appropriate structure and settings for the control system can often be derived directly¹¹¹. Furthermore, the model can be used to run simulations to determine the effect of changes in the controller, and in the person, on the controlled behaviour. In order to effectively use the dynamic model of people's behaviour during design and simulation, not only the average dynamics are important, but also the variability within and between individuals.

The dynamics of the speed changes following changes in prescribed step frequency are currently unknown. However, results of recent locomotion studies do allow us to make

predictions regarding these dynamics. For example, we found that the majority of step frequency changes following changes in speed occurred within in a few steps, followed by a slower convergence onto the preferred frequency^{69,70}. O'Connor & Donelan⁷¹ found similar mechanisms when studying the influence of visual perturbations on walking speed—they showed that following a perturbation to visually perceived walking speed, people rapidly changed their walking speed to bring their visually perceived speed back to their preferred, but then slowly drifted back to their actual preferred speed. Although these findings suggest that a fast and a slow process are present in the selection of preferred gait patterns, at least in certain contexts (all mentioned studies were performed on a treadmill) and when certain perturbations are applied, it remains to be tested whether similar processes are present in the selection of preferred walking speed when the only constraint is to synchronize steps to the beat of a metronome. Also, even if similar processes are present in the selection of overground speed, the precise timing of these processes might still be different due to changes in task mechanics.

We had two main goals for this study, with the first focused on determining the viability of open-loop control, and the second focused on quantifying the speed response dynamics required for designing a closed-loop control system. To determine the accuracy that can be expected when using an open-loop control system, we determined the variability in the steady-state relationship between prescribed step-frequency and speed, both within and between participants. We tested this variability under controlled conditions, because this will establish an upper bound on the performance that can be expected. To quantify the dynamics of the speed response following changes in prescribed frequency, we perturbed subjects step frequency using rapid changes in metronome frequency and measured their transient speed response towards their preferred speed. We then used system identification techniques to characterize these responses. Based on previous results, we hypothesized that both a fast (on the order of 2-seconds) and a slow (on the order of 30-seconds) process would be present in the selection of preferred speed⁶⁹⁻⁷¹. Because our results would be used in Chapter 4 to design a closed-loop speed control system we were not only interested in the average response, but also in the variation within and between individuals.

Methods

We performed two experiments to determine the dynamics underlying walking and running speed selection, respectively. Eight healthy young adults (4 men, 4 women; age 24 ± 2 years; leg length 0.82 ± 0.03 m; mean \pm SD) participated in the walking experiment. Sixteen healthy adults (14 men, 2 women; age 28 ± 7 years; weight 72 ± 10 kg; leg length 0.91 ± 0.03 m; mean \pm SD) participated in the running experiment. Prior to the experiments, we familiarized participants to the equipment and the experimental conditions by having them walk or run to a range of metronome frequencies for a minimum of ten minutes. Both single day experiments were performed on a standard 400-meter athletics track⁸³. The Simon Fraser University's Office of Research Ethics approved the protocol, and participants gave their written informed consent prior to the experiment.

Experimental setup

We measured running speed using a GPS-based speed sensor designed for high-accuracy speed sensing (VBOX Speed Sensor, Racelogic, UK), and step frequency using force-sensitive resistors mounted below the participant's heels in the walking experiment, or forefoot in the running experiment. The metronome frequencies were generated using an Arduino Uno microcontroller (Arduino, Italy), and communicated to the participants using Sony MDR-AS20J sport-specific earphones (Sony, Japan). The duration of each metronome beat was 100ms, the pitch of the metronome was 490Hz, and the amplitude of the metronome signal was adjusted based on participants' preference. All data were logged at 10 Hz using a second Arduino Uno microcontroller. The GPS and Arduino's were mounted onto the frame of a lightweight backpack that was worn by the subject during the experiment (total mass: 1.5 kg, figure 2.1).

Prior to the experiment, we verified the accuracy of the speed sensor by determining the average and instantaneous speed error. To determine the average error, we walked and ran a known distance at various speeds and compared the integrated speed measurement to the actual distance. The resulting average speed error was 0.2 ± 0.4 % (mean \pm SD). To determine the instantaneous error in speed measurement, we mounted the speed sensor to a cart instrumented with an optical encoder that allowed for precise speed measurement. We then pushed this cart around the track while walking and running at various speeds. We applied a one hertz Butterworth filter to both the GPS and

encoder data to reduce within-stride speed variations. After shifting the GPS data by the measurement delay (0.16 ± 0.08 s, determined from the peak in cross-correlation between encoder and GPS data), the root-mean-square-error between the GPS and encoder data was 0.8 ± 0.5 % (mean \pm SD). These results show that the speed sensor indeed accurately measured both the average and instantaneous speed.

Experimental protocol

Since slight methodological differences existed between the walking and running experiment, we will describe the details of both experiments separately. In both experiments we instructed subjects to synchronize their steps to the beat of the metronome. We also told them that the metronome frequency would change periodically.

Walking experiment

Before performing the step frequency perturbation experiment, we first determined participant's preferred step frequency while walking on a treadmill at 1.0 and 1.5 m/s. These step frequencies were then used as the base frequencies during the step frequency perturbation experiment (figure 3.1). This experiment consisted of four series of eight rapid changes in metronome frequency to and from the participant's base frequencies (two series at each base frequency). Between each perturbation the metronome frequency was maintained constant for 90 seconds. We applied both increases and decreases in metronome frequency, and used two different perturbation magnitudes (± 15 , ± 30 %). The order of perturbation directions and magnitudes was randomized between trials and subjects.

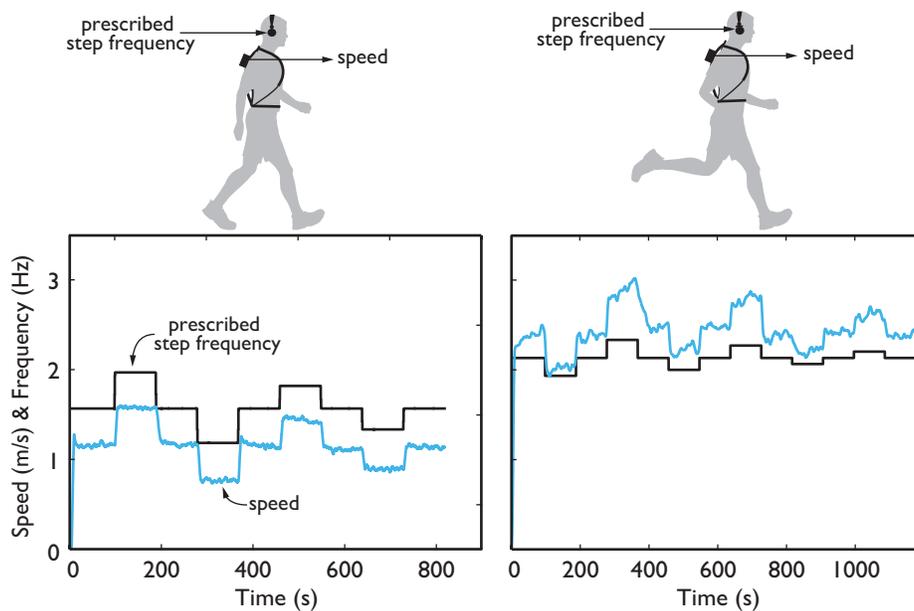


Figure 3.1 Experimental setup and time series data of the experimental protocol
 Subjects walked (left) or ran (right) overground while synchronizing their steps to a metronome. Metronome frequency was changed rapidly every 90-seconds. We measured the response in walking and running speed using a very accurate GPS-based speed sensor, carried by the subjects on a small backpack.

Running experiment

Before performing the step frequency perturbation experiment, we first determined the participants preferred step frequency by measuring their step frequency during an 800m self-paced run at their preferred speed. We suggested subjects to run at a comfortable 10km pace, and told them that they would have to be able to sustain this tempo for two times twenty minutes during the remainder of the experiment. The actual step frequency perturbation experiment consisted of two series of twelve rapid changes in metronome frequency to and from the participant's preferred step frequency (figure 3.1). Between each perturbation the metronome frequency was maintained constant for 90 seconds. We applied both increases and decreases in metronome frequency, and used three different perturbation magnitudes (± 4 , ± 8 and ± 12 bpm). The order of perturbation directions and magnitudes was randomized between trials and subjects.

Data analysis

For both experiments, we first divided each series of perturbations into individual frequency perturbations and their corresponding speed responses. We refer to these input-output pairs as trials.

Steady state relationship

We determined the steady-state relationship between prescribed step frequency and speed for each subject by first averaging the speed during the final 30 seconds of each trial. We then fitted these average speeds with a linear polynomial fit using the prescribed frequency as the independent variable. To determine the accuracy of an open-loop control system, we calculated the expected pacing error from the difference between the frequency-speed relationship and the actual measured speed for each frequency (i.e. the residuals). To establish an upper bound on the expected open-loop pacing accuracy we compared each participant's actual measured speed with their individual frequency-speed relationship—this reflects a scenario where the open-loop control system would be calibrated for each user individually.

Dynamic response

To be able to compare the dynamic response of perturbations of varying direction and magnitude, we normalized the perturbation and response data to zero before the perturbation and one after the perturbation. We defined zero as the average of the 30 seconds of data immediately prior to the perturbation, and one as the average of the trial's final 30 seconds of data.

Based on the results of our earlier findings, where we showed that the response in step frequency was well described by the combined actions of a fast and a slow process^{69,70}, we focused on the following two-process system to model the dynamics involved in the selection of preferred speed following a change in metronome frequency:

$$Y(s) = \left[\left(\frac{A_f}{\tau_f s + 1} \right) + \left(\frac{A_s}{\tau_s s + 1} \right) \right] e^{-T_d s} \cdot X(s) \quad (3.1)$$

where $X(s)$ is the input and $Y(s)$ is the output in the frequency domain (figures 3.2A–C). The parameters τ_f and τ_s represent the time constants of the fast and slow processes. The parameters A_f and A_s represent the amplitudes of the fast and slow processes, which we use to determine their relative contributions. We constrained the amplitudes to sum to one by enforcing $A_s = 1 - A_f$. The parameter T_d is a time delay to account for physiological time delays. We have previously proposed that this compound response might be explained by a combination of a fast predictive and a slow optimization process, which act together to minimize the energetic cost during walking and

running^{69,70}. The behaviour of this two-process system is perhaps most easily visualized when the input is an instantaneous step function—the output is then the sum of two exponential functions, one that converges to steady-state quickly and one that converges to steady state slowly (figure 3.2D).

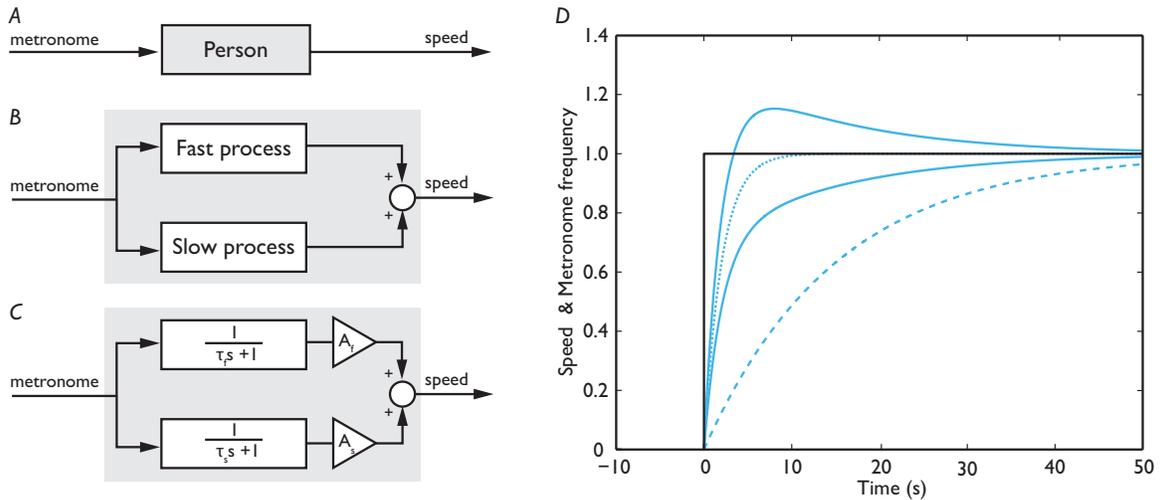


Figure 3.2 Two-process system and possible responses

A) To determine the dynamics underlying speed selection following changes in prescribed step frequency we treated the person as a dynamic system that can be identified by providing controlled inputs to the system and measuring its dynamic response. B) Based on our previous walking research, we hypothesized that a combination of a fast and a slow process underlie the selection of preferred speed in walking and running. Note that the parallel realization shown here is one of many different possible realizations of the second order system described in equation 3.1, and is only included here as an example. C) Mathematically, these processes can be represented by two transfer functions that act on two different time scales. D) Illustrations of the possible system responses to a step input. If only the fast process is active, the system rapidly reaches steady-state and never overshoots the steady-state value (dotted line). If only the slow process is active, the system gradually approaches the steady-state value (dashed line). If both processes are active, the fast process can result in the system either initially undershooting or overshooting the steady-state value (solid lines). The slow process will cause the system to gradually converge to the steady-state value. Whether an overshoot or undershoot occurs is determined entirely by the relative contribution of the 2 processes, which is determined by their amplitudes (A) and not by their time constants (τ).

We estimated the model parameters using a least-squares optimization routine. We first attempted to fit all trials individually, to obtain trial specific estimations of the time delay, time constants and amplitudes. This procedure worked well for estimating the fast process, but for the slow process the results were highly variable. The reason for this inaccuracy is that there is actually very little information present in the data to fit the slow process, because the fast process described most of the changes. Hence, the cost function for individual trials often did not contain a clear minimum in the direction of the slow process, and often multiple local minima existed. Fitting multiple exponentials to noisy time series data is actually a well-known problem—the fit of data by a sum of

exponentials, and in particular by real exponents, may be very badly conditioned resulting in large changes in best-fit parameters with only small changes in data¹¹². Our solution was to fit all trials per participant at once, while constraining the time constants to be equal for all trials but allowing the amplitudes to vary for each individual trial. Allowing the amplitudes to vary between trials allowed us to fit various response types as found previously when studying the selection of preferred step frequency and walking speed, such as undershoot and overshoot responses^{70,71} (figure 3.2D). By constraining the time constants to be equal between all trials for a particular subject the influence of the noise present in each individual trial on the best-fit parameters was decreased, resulting in a more consistent estimates of the slow time constant.

As considerable noise was present in the data, we decided to place more emphasis in the fitting procedure on trials with a lower signal-to-noise ratio. To this effect, we weighted the contribution of each trial to the objective function by the inverse of the standard deviation of the noise present in each trial after normalization. We estimated the noise within each trial by first fitting a smoothing spline to each trial, from 20 seconds past the perturbation to the end of the trial. The smoothing parameter (*SP*) of the spline fit was determined a-priori from data of a subject running freely while maintaining their speed as constant as possible. This parameter was chosen so that the fit accurately followed the slow speed changes, but ignored the higher frequency fluctuations ($SP=10^{-5}$, figure 3.3). One downside of using our weighting procedure compared to a non-weighted fit is that frequency perturbations of higher magnitude are weighted more heavily, because the signal-to-noise ratio is necessarily higher in these trials. However, these trials also contain the most reliable information regarding the processes of interests. Furthermore, we found that our main findings would not have been significantly different had we used a non-weighted procedure.

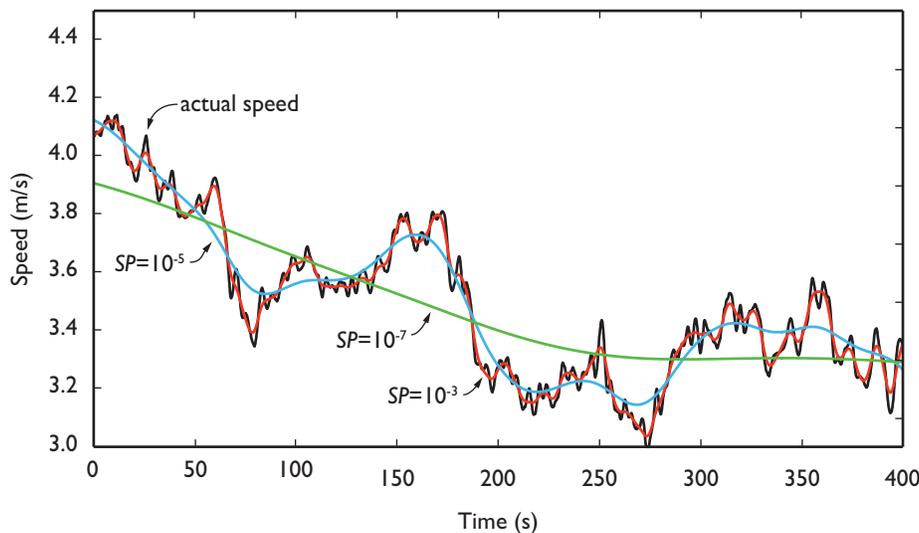


Figure 3.3 Estimating noise from the data

Each trial was too short to allow for accurate noise estimation while the subject's speed was in steady state. We determined the noise present in each trial from a portion of the trial where speed was still changing slowly. To ensure that none of these slow speed changes would be considered noise, we first fitted a smoothing-spline to each trial. We then subtracted this spline fit, and considered the remaining variability as noise. The smoothness of the spline-fit, and thus the noise estimate, depends on the value of the *smoothing parameter* (SP). This parameter was selected a-priori from data of subjects running freely while attempting to maintain their speed as constant as possible. We selected the smoothing parameter so that the slow changes in speed were followed accurately, while the higher frequency changes were ignored. Example data of a subject running freely and smoothing-splines for three values of the smoothing parameter are shown. The speed noise would be underestimated when using $SP = 10^{-3}$, because it follows the actual speed too closely. The variability in speed would be overestimated when using $SP = 10^{-7}$. Since it does not follow the slow changes in speed, these slow changes would be considered noise as well. Here we used $SP=10^{-5}$ because it follows the slow changes in speed, but not the higher frequency fluctuations.

The objective function to be minimized in the least-squares optimization was the sum of the squared difference between measured data and model predictions within each trial, summed across trials. The optimization procedure minimized the objective function using the Levenberg-Marquardt algorithm¹¹³, implemented with MATLAB's *lsqcurvefit* function. To avoid convergence problems associated with parameter optimization in time-delayed systems^{114,115}, we visually estimated each trial's time delay by identifying when the speed following a frequency perturbation first exceeded the speed fluctuations observed during steady state, and removed this delay prior to performing the optimization. Hence, the reported time delays were visually determined, and were not part of the optimization outcome. Before estimating the model parameters, we removed trials where the change in speed following the frequency perturbation was within the measurement noise, where the noise was estimated as illustrated in figure 3.3. We removed 1 out of 256 trials (0.4%) in the walking experiment, and 43 out of 312 trials (13%) in the running experiment.

Statistics

We performed a bootstrap procedure to determine confidence bounds for the time constants and average amplitude of the fast process for each participant. Bootstrapping is a well-accepted statistical technique used to determine the distribution of a sample statistic in those cases where it is complicated, or impossible, to determine this distribution using conventional statistics^{86,116}. The basic procedure in bootstrapping is to resample, with replacement, the original dataset many times, and to calculate bootstrap replications of the statistic of interest from these bootstrap samples (figure 3.4A). The result is an empirical distribution of the statistic of interest within the sample data (figure 3.4B). The assumption underlying the bootstrap procedure is that this empirical distribution closely resembles the true distribution of the statistic of interest. Here, we performed the bootstrapping procedure by first randomly selecting n trials from the full set of trials for one subject, where n equalled the original number of trials. Since we selected trials with replacement, the same trial could end up multiple times in a bootstrap sample. We then fitted the two-process model, using the method described above, to this bootstrap sample. This was repeated 1000 times for each subject, resulting in 1000 estimates of the fast and slow process and average fast amplitude for each subject¹¹⁶. From these empirical distributions we determined the 95%-confidence interval as the interval between the 2.5th and 97.5th percentiles¹¹⁶.

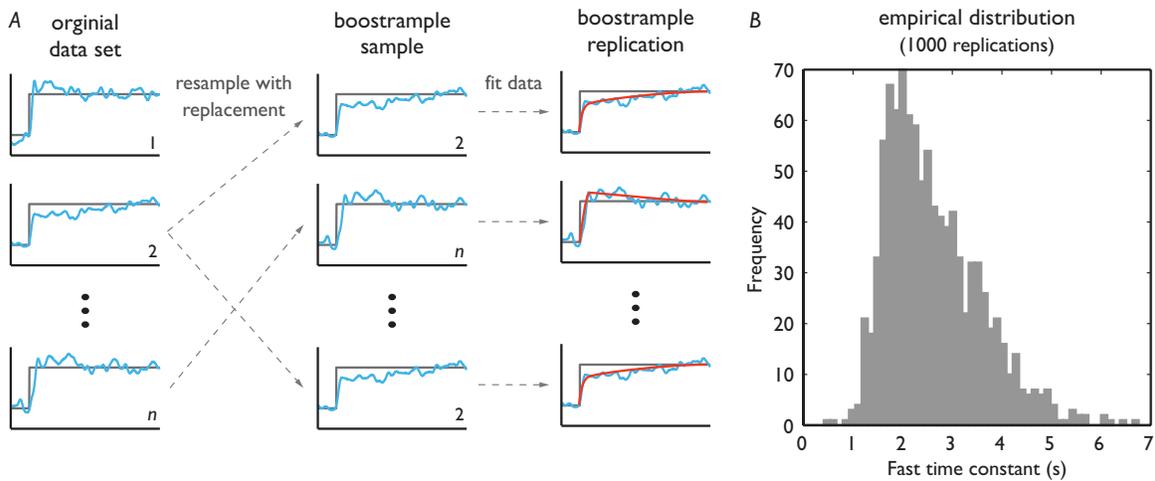


Figure 3.4 Bootstrap procedure

We used a bootstrapping procedure to determine the confidence intervals for the fast and slow time constants and the average fast amplitude. A) Schematic of the bootstrap process. We generated 1000 bootstrap samples from the original data set for each subject. Each bootstrap sample had the same number of trials as the original data set, and was generated by sampling n times with replacement from the original data set for that subject. Bootstrap replications for the two-process model parameters were obtained by fitting the two-process model to each bootstrap sample. B) Example outcome of the bootstrap process for the fast time constant for a representative subject. We calculated the 95%–confidence interval directly as the interval between the 2.5th and 97.5th percentile of the data in the resulting empirical distribution. We felt this was safer than assuming a normal distribution, which is not supported by this bootstrap sampling.

We used non-parametric statistical tests to test for significant differences for two reasons. First, due to the relatively small sample sizes used in the experiments, it was not possible to confirm that the population data of the parameters of interest was normally distributed. Second, for some parameters of interest it was actually highly unlikely that the population would be normally distributed (for example the fast time constant, which has an average value fairly close to zero, but cannot be negative). For paired-sample tests we used Wilcoxon signed-rank test⁸⁵, for individual-sample tests we used Wilcoxon rank-sum test⁸⁵. We used Chi-square tests to determine whether specific subjects, specific perturbation directions or specific perturbation magnitudes were more likely to exhibit undershooting or overshooting patterns⁷⁰. When a significant effect was found we used pairwise Chi-square tests to determine what pairs were significantly different. In this case, the p-value was adjusted using Bonferroni correction to reduce the chance of a type I error. We considered a probability less than 0.05 as significant.

Results

Between the two experiments, three out of 24 participants (13%) were unable to synchronize their steps to the metronome. Even after substantial practice a persistent

difference existed between the prescribed frequency and these participants' actual step frequency. We aborted the experiment for those participants. All three participants were in the running experiment—none of the participants in the walking experiment had problems synchronizing their steps to the metronome.

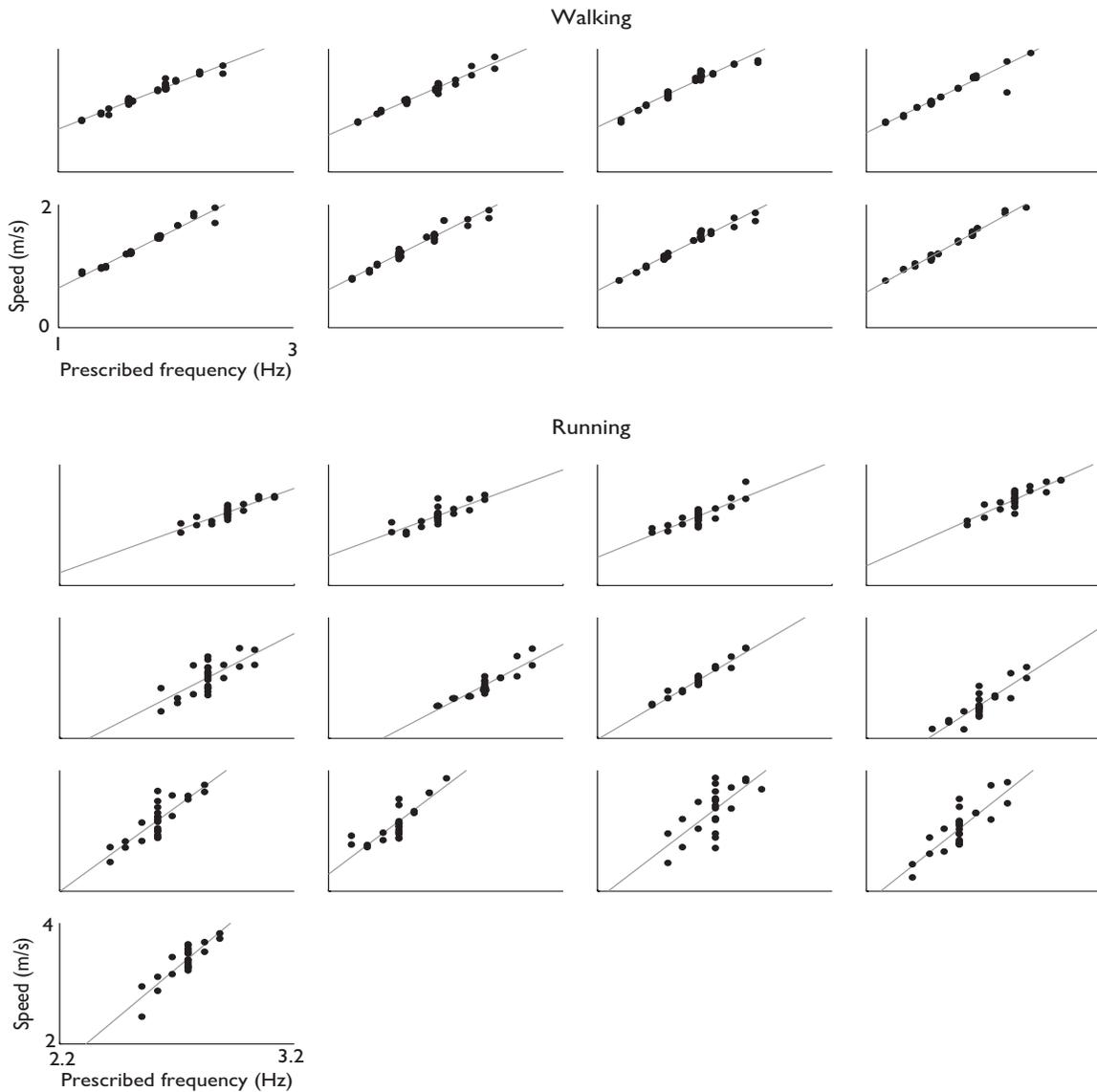


Figure 3.5 Frequency-speed relationship for all participants
Steady state relationship between prescribed step frequency and speed for each subject in both the walking and running experiment, including best-fit linear polynomials.

Steady-state relationship

The steady-state relationship between prescribed step frequency and preferred speed was well described by a linear relationship in both walking and running (figure 3.5). The coefficient of determination of the linear relationship (R^2) was 0.96 ± 0.02 for walking and 0.73 ± 0.11 for running. The average slope of the linear relationship was $0.9 \pm 0.1 \text{ ms}^{-1}/\text{Hz}$ for walking and $2.3 \pm 0.7 \text{ ms}^{-1}/\text{Hz}$ for running (figure 3.6). The goodness-of-fit of these relationships only marginally improved when using a second order polynomial instead of a linear polynomial (R^2 : 0.96 and 0.75 for walking and running, respectively), indicating that a linear function is sufficient to capture the relationship between prescribed frequency and speed for the speed ranges used here.

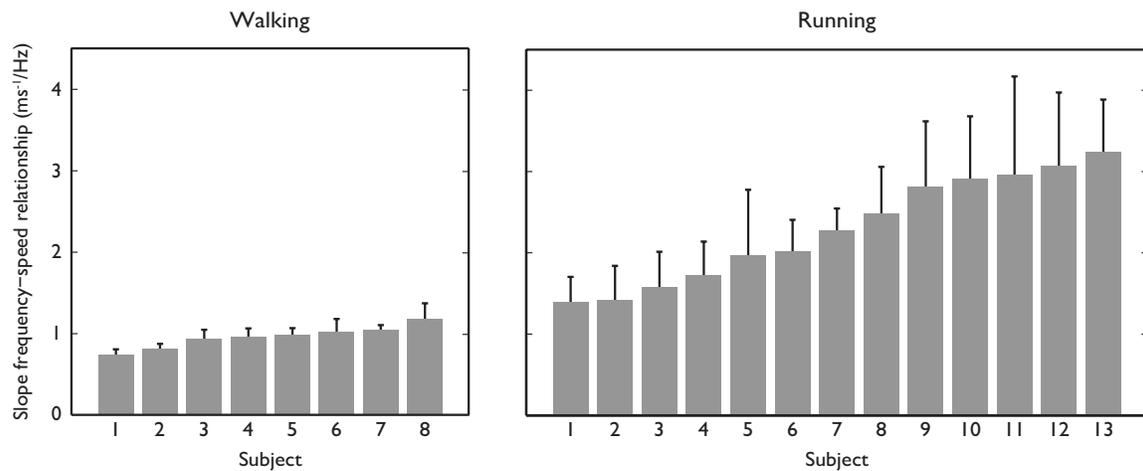


Figure 3.6 Step frequency–speed relationship slope

Average slope of the frequency–speed relationship in walking (left) and running (right) for each subject. Error bars are 95%–confidence intervals.

The average absolute deviation between each participant’s actual measured speed and their individual preferred relationship was $2.7 \pm 3.0\%$ in walking, and $3.7 \pm 3.2\%$ in running. Note that we used the absolute value of the residuals when calculating this deviation, because per the definition of a least-squares fit the ‘regular’ average of the residuals is zero⁸⁵. When including the sign of the errors, we found that the residuals of all participants grouped together were distributed normally around zero (walking: $p=0.59$, running: $p=0.12$, Kolmogorov-Smirnov test) with a standard deviation of 4.1% in walking and 4.9% in running.

Dynamic response

We found that the majority of the changes in walking and running speed following a change in prescribed frequency were rapid. In both experiments, subjects responded to perturbations by first rapidly changing their speed towards their preferred speed, and then slowly fine-tuning their speed (figure 3.7). These dynamics were well captured by the sum of a fast and slow process (equation 3.1), that had large and significant differences in their time constants (figure 3.8). Specifically, the fast and slow processes underlying speed selection had respective time constants of 1.7 ± 0.3 s and 26.7 ± 5.8 s in walking ($p = 7.8 \times 10^{-3}$), and 1.9 ± 0.8 s and 30.5 ± 6.4 second in running ($p = 2.4 \times 10^{-4}$, Wilcoxon signed-rank test). Comparing time constants between the walking and running responses showed that no difference existed between the fast processes ($p = 0.49$) and slow processes ($p = 0.23$, Wilcoxon rank-sum test). Subjects exhibited similar but statistically different delays prior to responding to the perturbations, with 1.2 ± 0.4 s in the walking experiment and 1.6 ± 1.7 s in the running experiment ($p = 1.0 \times 10^{-3}$; Wilcoxon rank-sum test).

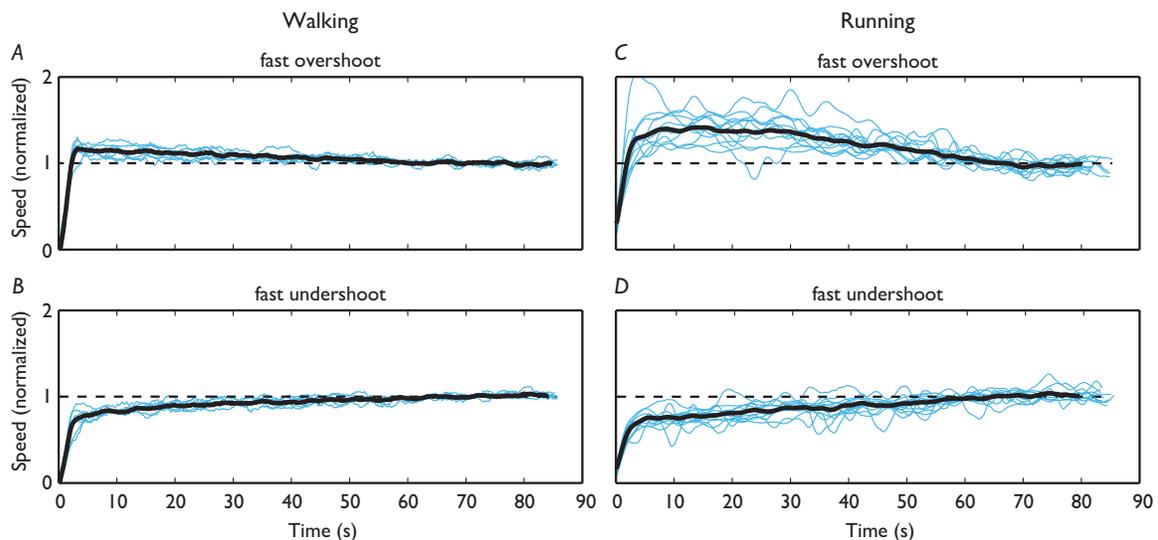


Figure 3.7 Average speed responses to changes in metronome frequency

Average speed responses to changes in metronome frequency for walking (left) and running (right). The blue lines are averaged responses for each subject. The black lines are averaged responses across all subjects. A) Average responses for walking trials that initially overshoot the steady-state speed. B) Average responses for walking trials that initially undershot the steady-state speed. C) Average responses for running trials that initially overshoot the steady-state speed. D) Average responses for running trials that initially undershot the steady state-speed.

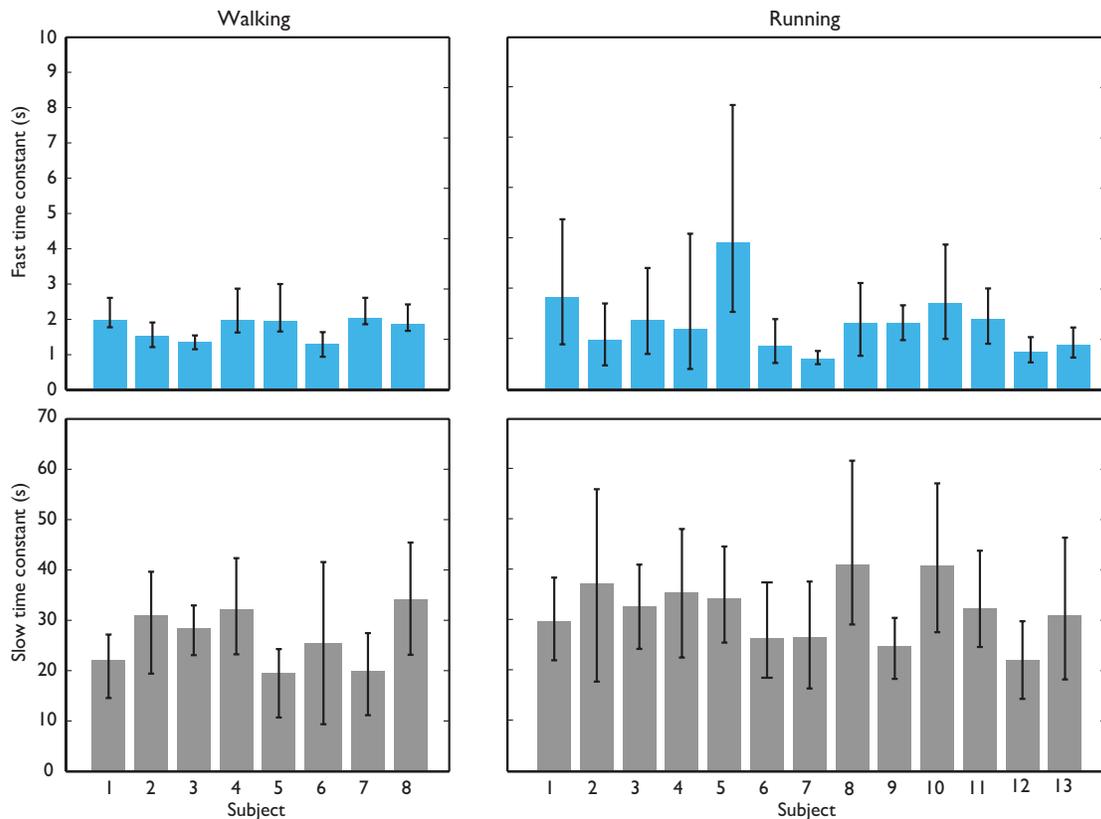


Figure 3.8 Dynamics of the speed response to changes in metronome frequency
 Identified time constants for the two-process model in walking (left) and running (right). Error bars are 95%–confidence intervals. Because the error bars were estimated from the results of the bootstrap procedure instead of assuming normally distributed data, the error bars are not guaranteed to be symmetric. Hence, two sided error bars are shown.

The fast process dominated the adjustments in both walking and running speed. The average fast process amplitude was 1.0 ± 0.1 in walking and 1.2 ± 0.3 in running (figure 3.9). On average, the fast process amplitude was not different from one in walking ($p=0.29$) or running ($p=0.14$), respectively. Since the slow process was defined as one minus the fast process, the average slow process was not different from zero. Thus, on average, the fast process rapidly and accurately adjusted speed toward the final steady state value requiring little fine-tuning adjustments from the slow process. However, this average response does not accurately convey how the relative contributions of the two processes varied from trial to trial. For example, the fast process amplitude varied between 0.4 and 1.6 in the walking experiment, and between -0.2 and 2.4 in the running experiment (95%-confidence interval). Fast process amplitudes greater than one indicate initial adjustments that overshoot the final steady state value, while those less

than one indicate initial responses that undershot the steady state value (figure 3.7). In both *fast overshoot* and *fast undershoot* trials, the slow process contributed the remaining adjustments to slowly converge the subject to steady state. In some trials, the initial response did not overshoot or undershoot but brought the subject very close to the preferred steady state gait yielding a fast process amplitude close to one. In these *fast accurate* trials—defined here as A_f between 0.95 and 1.05—the contribution of the slow process was small compared to the size of step-to-step variability in step frequency or speed. In the walking experiment, 37% of the responses were fast undershoot, 46% were fast overshoot, and 17% were fast accurate. In the running experiment, 44% of the responses were fast undershoot, 45% were fast overshoot, and 11% were fast accurate.

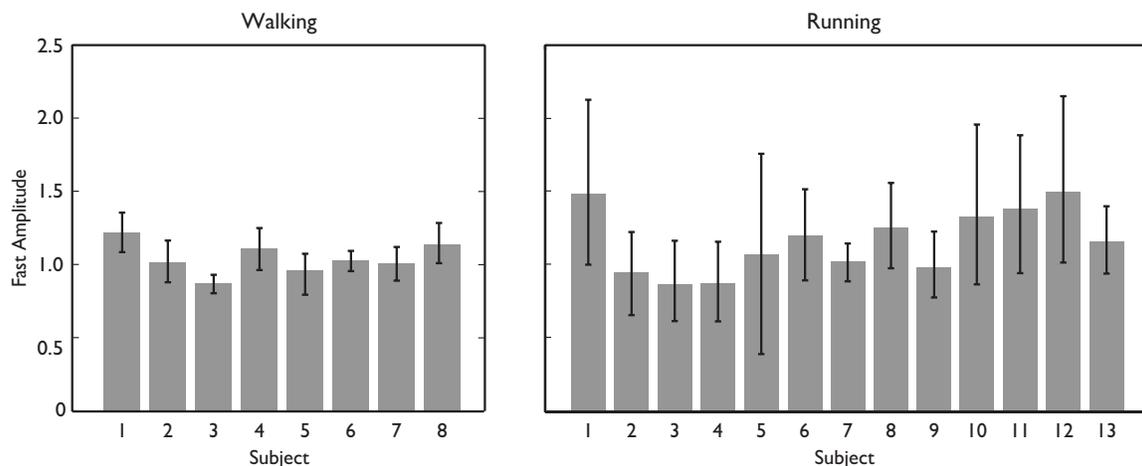


Figure 3.9 Amplitude of the fast speed response to changes in metronome frequency Identified average fast amplitude for the two-process model in walking (left) and running (right). Only the fast amplitudes are shown as the slow amplitudes were constrained to one minus the fast amplitude. Error bars are 95%–confidence intervals. Because the error bars were estimated from the results of the bootstrap procedure instead of assuming normally distributed data, the error bars are not guaranteed to be symmetric. Hence, two sided error bars are shown. Note that this is the amplitude of the normalized response, and is thus dimensionless.

We found that only in the walking experiment the distribution of the three response types (fast overshoot, fast undershoot and fast accurate) varied significantly between participants ($p=0.002$). We found that in both the walking ($p=0.03$) and running ($p=0.004$) experiment the perturbation magnitude had a significant effect on the fast response type. More specifically, in walking we found that participants exhibited more fast overshoot responses when the 15% perturbation was applied compared to when the 30% perturbation was applied, which resulted in more fast accurate and fast undershoot responses. In the running experiment we found that when a step frequency perturbation

of 4 bpm was applied a larger number of responses were fast undershoot compared to when an 8 bpm perturbation was applied, which resulted in more fast accurate and fast overshoot responses ($p=0.0006$). We did not find any effect of perturbation direction on fast response type.

The two-process model well described the speed responses to frequency perturbations in both experiments. However, this is not well captured in the R^2 value for each individual fit. Since the noise present in walking and running speed was high relative to the speed responses following the frequency perturbations, the R^2 values for the individual fits were quite low (walking: 0.48 ± 0.23 , running: 0.31 ± 0.23).

To get better insight into how well the two-process model described the perturbation responses, we determined how well the response times from the individual fits described the average perturbation response for each subject. For this purpose, we first averaged the fast undershoot ($A_f < 0.95$) and fast overshoot responses ($A_f > 1.05$) for each subject individually (figure 3.7), and fitted these data using the previously determined time constants while allowing the amplitudes to vary. This averaging reduced the contribution of noise, because, from trial to trial, this noise is uncorrelated with perturbation onsets. The R^2 -values for the average fast undershoot and fast overshoot data in the walking experiment were 0.89 ± 0.06 and 0.86 ± 0.06 , respectively. The R^2 values for the average fast undershoot and fast overshoot data in the running experiment were 0.70 ± 0.16 and 0.72 ± 0.17 , respectively. These results indicate that the two-process model well described the dynamics of speed selection in both walking and running.

Discussion

Our findings suggest that open-loop control of overground speed would, at best, provide a small improvement over people's ability to pace them selves. Here we found that the expected open-loop pacing error in running is 3.7%. This is only a marginal improvement over the 4% pacing error in recreational runners when not using any pacing devices (Chapter 2). Thus, at least in running the improvement in pacing accuracy would be small when using an open-loop speed control system. Unfortunately we are not aware of any studies quantifying the pacing error during walking, nor did we test it ourselves. The open-loop pacing error found here is a 'best-case' scenario, because it is based on individually determined relationships between step frequency and speed, and the data

were collected under highly controlled conditions (i.e. no, or at least very small, influences of terrain, wind, footwear, etc.). One factor that might improve the pacing accuracy over the accuracy found here would be increased practice. However, this would mean that user's will not get the benefits of the pacing device immediately. Our findings do not mean that open-loop pacing is not useful—if the only desire is to control workout speed qualitatively (e.g. speed up, slow down), open-loop control can be very useful.

We expect that a closed-loop speed control system would perform significantly better because the performance would depend less on an estimated relationship between frequency and speed. Such a closed-loop speed control system would however need to be able to deal with significant variations within and between individuals. As hypothesized, the average speed response in both walking and running was described well by the previously proposed two-process model. However, considerable variability around this average behaviour existed in individual trials.

This variability, in theory, does not have to affect the accuracy of a closed-loop control system. The variability found here might influence the time it takes for the user's speed to converge to the desired speed, but as long as the user is able to keep up with the metronome they will converge eventually. Basically, as long as a difference between the desired and the actual speed exists, the system will simply keep adjusting the prescribed frequency. To ensure robust performance for a large range of users, it is certainly important to take the variability found here into account when designing the speed control system.

Our finding that the majority of the changes in speed following changes in prescribed step frequency occur rapidly has a positive effect on the performance that can be expected from a closed-loop control system. Ideally, the person's speed would change rapidly following changes in the target speed, and effects of external perturbations would be corrected quickly. The change in prescribed frequency required to elicit these desired responses strongly depends on the speed response dynamics. Given that speed naturally changes quickly (figure 3.10A), gradual changes in metronome frequency are sufficient to elicit a fairly rapid response (figure 3.10B). In contrast, had we found that speed naturally changes quite slowly (figure 3.10C), the only way to achieve a reasonable fast response would be to largely *overshoot* the frequency of the metronome

signal (figures 3.10D). Even if the user would be able to keep up with such fast metronome frequencies, making it technically possible to produce the desired speed response, the required changes in metronome frequency would likely be uncomfortable. Basically, the natural dynamics set a constraint on the performance of the control system that can be anticipated. Given our finding that the majority of these dynamics are fast, it should in theory be possible to elicit fast speed responses while using gradual changes in prescribed frequency.

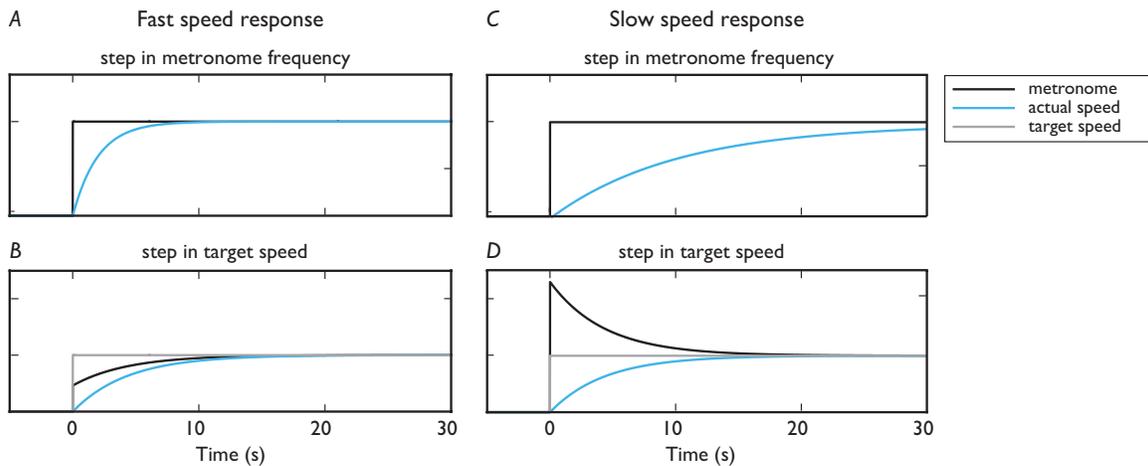


Figure 3.10 Controlling speed of a person with a fast versus a slow response

A) Speed response of a fast responding person (time constant: 2 s) following a step in metronome frequency. B) Response of the person in A to a step in desired speed. C) Speed response of a slow responding person (time constant: 10 s) following a step in metronome frequency. D) Response of the person in C to a step in desired speed. For the control system to elicit the desired speed response (desired settling time: 10 s), in the fast system the metronome signal gradually converges onto the final value. However, to elicit the same response in the slow system the metronome signal needs to considerably overshoot the final value. This overshoot in metronome frequency is not desirable, as it is likely to be uncomfortable to the user in that they will be required to make a very large and rapid change in their step frequency. Furthermore, the change in step frequency may simply be too fast to be physiologically possible.

The variability in the speed response following a frequency perturbation was considerably higher in running compared to walking, as reflected by the lower R^2 values for the two-process fits, and the wider confidence intervals for the fast time constant, time delay and fast process amplitude. One explanation for the increased variability during running would be that subjects were not as well able to synchronize their steps to the metronome in running compared to walking. This does not appear to be the correct explanation—the root-mean-square error between the metronome frequency and the actual frequency was comparable between the walking (0.05 ± 0.03 Hz) and running experiment (0.05 ± 0.02 Hz, $p = 0.03$, Wilcoxon rank-sum test).

A second possible explanation for the higher variability during running is that this variability reflects a fundamental difference between walking and running. The less clearly defined relationship between prescribed step frequency and speed in running might be the result of a difference in the cost function underlying the mapping between step frequency and speed. Intuitively, the cost function can be understood as the reason why a relationship between prescribed frequency and speed exists in the first place (e.g. energetic cost, local fatigue, stability, etc., or any combination of these factors). It has been proposed that energetic cost plays an important role in the cost function underlying the frequency-speed relationship, in both walking and running^{40,41,68}. One reason that the relationship between step frequency, speed, and energetic cost is more variable between individuals in running is that it might have a higher dependency on fitness level. Anecdotally, we found that the slope of the frequency-speed relationship in two highly trained athletes was indeed steeper than the steepest slope found in our population of recreational runners. A second reason for the increased variability could be that energetic cost has a smaller role in the cost function in running compared to walking—perhaps (local) fatigue, stability, or psychological factors such as motivation are increasingly important. The increased variability in running might then be a reflection of the higher variability in any of these factors. We propose that determining individual's frequency-speed relationship under varying conditions might provide further insight in the role of energetic cost minimization in the control of locomotion.

We found that the majority of changes in speed following a change in prescribed step frequency occur rapidly. This is identical to what we have previously found when studying the physiological selection of preferred step frequency following perturbations in treadmill speed^{69,70}. The similarity between the physiological selection of preferred speed and step frequency, despite the differences between the nature of the perturbation (sensory vs. physical) and context (overground vs. treadmill walking), suggest that the same two processes govern the selection of step frequency and walking speed. The faster of the two processes rapidly adjusts speed, bringing people toward their preferred speed within a few steps. The slower process takes considerably longer, fine-tuning speed to slowly converge people to their steady state gait. These collective findings strongly suggest that these two processes reflect common control mechanisms for selecting gait patterns that are preferred given the environmental and task constraints in which the person needs to operate.

Although our results strongly suggests that a slow process is present in the selection of walking and running speed, the exact time constant of this slow process might be influenced by our fitting procedure and needs to be interpreted with caution. Given the moderate contribution of the slow process to the overall response, combined with the relatively high variability in speed, it was not possible to reliably fit the slow process without forcing the amplitudes of the slow and fast process to sum to one. Had we collected more than 90-seconds per frequency there would have been more data available to fit the slow process, rendering this artificial constraint unnecessary. For future studies we recommend that each frequency be maintained for at least three minutes between perturbations to allow enough time for each subject to reach steady state. Unfortunately, the time between perturbations would limit the amount of trials that can be collected in a single experimental session. Especially due to the relatively high variability between responses collecting many trials is beneficial to help find the patterns of interest.

A second limitation introduced by our protocol was that subjects did not always reach steady state for each prescribed step frequency, thereby limiting our ability to accurately estimate the amount of speed variability present when synchronizing steps to the beat of a metronome. An accurate estimate of the speed variability would have been interesting, especially for comparison with the behaviour of an eventual speed control system (as it would provide insight into how much the speed control system would increase or decrease this variability). We recommend adding at least one extra minute (to the previously recommended three minutes) if the goal is also to estimate variability in steady state walking.

Our study had a number of other important limitations. First, in retrospect it might have been better to allow participants more time to get used to synchronizing their steps to the metronome, especially during running. More practice might have reduced the variability found in the results, thereby further highlighting the patterns of interest. However, the current finding that speed responses are variable is valuable information, especially for our future goal of developing an overground speed control system. Furthermore, because most participant's had no problem synchronizing their steps to the metronome, any benefits resulting from more practice would be expected to be due to an improved mapping between speed and frequency. Currently, it is unknown whether such

improvement is indeed possible, and how much time this would require. Second, in the running experiment our participants were predominantly males. As differences in body dynamics between males and females might result in different speed response dynamics, it would have been preferable to include more females in this study. Thus, it would be desirable to confirm our findings in a population including more females. Finally, our finding that the relationship between prescribed step frequency and speed is close to linear is likely due to the range of speeds used here. Had we used a larger range of walking and running speeds it is likely that a higher order relationship would have been required to accurately describe the data⁴¹.

In conclusion, we found that an open-loop speed control system is unlikely to offer significant improvements in pacing accuracy relative to self-paced locomotion. We also found that the dynamic response in walking and running speed following changes in prescribed step frequency is comparable to what we found previously when studying the frequency response following changes in speed^{69,70}. Our finding that the majority of the changes in speed occur within a few steps following a change in metronome frequency suggests that a control system can generate rapid speed adjustments while using gradual changes in prescribed frequency. In Chapter 4 we will determine whether it is possible to improve the pacing accuracy over the open-loop accuracy found here by using a closed-loop control system. Such a speed control system might prove useful for improving running performance (Chapters 1 and 2), and as a rehabilitation tool for walking (Chapter 1), especially because synchronization with rhythmic stimuli often occurs spontaneously^{22,24,117}.

Chapter 4. Development and testing of a feedback controlled metronome for the accurate control of walking and running speed

Abstract

We have previously proposed that a system to accurately control overground walking and running speed could be useful for both exercise and gait rehabilitation. We have shown that it is likely that overground speed can be controlled accurately by prescribing step frequency (*auditory rhythmic pacing*), but that using a predetermined relationship between step frequency and speed does not result in accurate speed control (even when an individualized relationship is used). The purpose of this study was to develop and test a *closed-loop speed control system*, consisting of a feedback-controlled metronome that makes the prescribed step frequency a function of the difference between the target and actual speed. We used our previously determined dynamical model of walkers' and runners' speed response to changes in prescribed step frequency to find the control system topology and settings required for an accurate, responsive, robust, stable and comfortable control system. Our analysis demonstrated that a proportional-integral controller could deliver the desired speed response. The average difference between the target and actual speed, across all participants, was $0.7 \pm 0.4\%$ in walking and $0.6 \pm 0.4\%$ in running when using this controller. These results were achieved when using identical controller gains (*default gains*) for all participants in the walking and running experiment, although the controller gains were different between walking and running. However, when using these default gains, for some participants the time required for their actual speed to converge onto a new target speed (*response time*) was longer than our desired response time, especially in the running experiment. By adjusting the controller gains based on the slope of each participant's individual frequency-speed relationship (*individual gains*) we were able to significantly improve the response time for these participants. In conclusion, we demonstrated that it is possible to

accurately control overground walking and running speed by using auditory rhythmic pacing.

Introduction

Auditory rhythm has been used to prescribe movement tempo since earliest recorded times²⁰. One well-known example is the use of music to orchestrate the pace of soldiers. For this purpose, typically only two different tempi were used, either marching or running, resulting in a very coarse control of overground speed¹¹⁸. However, based on recent findings we have proposed that walking and running speed could potentially be controlled very accurately by prescribing the appropriate tempo (Chapter 3). As such overground speed control system could prove useful in a range of different situations (Chapter 1), the goal of this study is to actually develop such a pacing device and test its performance in both walking and running.

Two characteristics of the physiological selection of preferred speed suggest that rhythmic pacing can be used to accurately control overground speed. First, a strong positive relationship exists between prescribed step frequency and speed in steady state walking and running^{40,68,119}. As a consequence, whenever the prescribed step frequency is changed, it can be expected that speed will change also. For example, an increase in prescribed step frequency will generally result in an increase in speed. Second, most of these changes in speed occur within the first few steps following a change in prescribed step frequency (Chapter 3). This is important because it makes possible rapid adjustments in controlled speed and, thus, accurate tracking of the desired speed as well as efficient rejection of perturbations (Chapter 3).

In Chapter 3 we have shown that an *open-loop control system* would not be sufficient to accurately control speed. The functioning of such system relies on a model that captures the relationship between prescribed step frequency and speed (figure 1.1A). Hence, any variability in the relationship between frequency and speed that is not captured by this model results in differences between the desired and actual speed. In Chapter 3 we found that when using an open-loop control system the average absolute deviation between the desired speed and actual speed was 2.7% during walking and 3.7% during running. At least in running this is a marginal improvement over the 4% pacing error recreational runners make on average when not using any device to help them regulate

speed (Chapter 1). Furthermore, these results were found in highly controlled conditions, and when using an individually determined model for each participant. Thus, these results place an upper bound on the accuracy that can be expected using open-loop speed control. Using the system in less controlled conditions, or using a single model for each user, would further decrease the accuracy.

We proposed that the accuracy of the speed control system could be improved by using a *closed-loop control system* instead (figure 1.1B). In such a system the prescribed step frequency is directly related to the difference between the desired and actual speed. Whenever a difference exists, the closed-loop system changes the prescribed step frequency in order to reduce this difference. Even if our understanding of the relationship between prescribed frequency and speed is not perfect, such a system could provide more accurate control. As a result, the same system could provide more accurate speed control in many individuals, despite differences between these individuals, and despite the presence of external perturbations.

Our goal for this study was to develop a closed-loop system to accurately control overground walking and running speed by prescribing the appropriate step frequency. Towards this goal, we leveraged our understanding of the physiological selection of preferred speed (Chapter 3) to design and develop a speed control system. We then tested the system in both walking and running by guiding subject's through a range of different overground speeds, and quantifying the system's performance.

Methods

Speed control system design

Our approach to designing the speed control system is described in detail in Appendix B. Here we will only present a brief summary of the design criteria and solutions. Our main design criteria for the speed control system were accuracy (good correspondence between target and actual speed), responsiveness (timely convergence of actual speed to target speed following a change in target speed), robustness (good performance despite uncertainty in the plant and/or external perturbations), stability (bounded inputs lead to bounded output) and comfort (smooth changes in the metronome signal).

Our analysis, presented in Appendix B, suggested that a proportional-integral (PI) controller could be used to develop a system that met our design criteria. Our analysis further suggested that it would be possible to achieve robust accuracy while using the same controller settings for each individual (*default settings*), but that the inter-individual variability present in the slope of the frequency-speed relationship would result in poor responsiveness for some individuals. That is, our analysis suggested that for some individuals the convergence onto a new steady-state speed following a change in target speed would be quite slow. However, our analysis suggested that it should be possible to reduce the effect of this inter-individual variability in the frequency-speed relationship by using controller settings that are adjusted using knowledge of each participant's frequency-speed relationship. Although here these *individual settings* were calculated off-line based on the data of an separate experiment, an adaptive control system could be used to update the controller settings in real-time based on the best estimate of the user's frequency-speed relationship up to that point in time. We tested the performance of the control system for each participant using both the default and individual settings. The desired response time used to determine the controller settings (the time required for the actual speed to converge onto the target speed) was 21 seconds in walking and 11.4 seconds in running. For walking, the final default controller settings were 0.13 and 0.10 for the proportional and integral gain, respectively. For running, the default proportional and integral gains were 0.06 and 0.05, respectively. The individual controller settings for each participant are given in table B-1.

Experiments

To test the performance of our speed control system in walking and running we performed two separate experiments. Five healthy volunteers participated in the walking experiment (2 men, 3 women; age 28 ± 3 years; weight 65 ± 16 kg; leg length 0.91 ± 0.08 m; mean \pm SD) and in the running experiment (4 men, 1 woman; age 33 ± 14 years; weight 75 ± 9 kg; leg length 0.91 ± 0.03 m; mean \pm SD). Most participants were not naïve to the speed control system, but had a general understanding of how the system worked. Both experiments were performed on a standard 400-meter athletics track⁸³. The Simon Fraser University's Office of Research Ethics approved the protocols, and participants gave their written informed consent prior to the experiments.

Experimental setup

We implemented the speed control system using custom written code on an Arduino Uno microcontroller, which was also used to generate the metronome signal. The duration of each metronome beat was 100ms, the pitch of the metronome was 490Hz, and the amplitude of the metronome signal was adjusted based on participants' preference. The metronome signal was communicated to participants using Sony MDR-AS20J sport-specific earphones (Sony, Japan). The proportional-integral controller was implemented in the ideal parallel (non-interacting) form¹²⁰. The control loop was updated ten times a second, based on speed measurements received from a GPS-based speed sensor (VBOX Speed Sensor, Racelogic, UK). Measured speed was first filtered using a 2-second median filter prior to using it in the control system, to reduce the influence of noise. We used a median filter to minimize the effect that brief, high-magnitude noise in speed measurement would have on the speed entering the control system. Due to the properties of the median filter such outliers are removed very effectively^{121,122}. We mounted a force-sensitive resistor underneath subjects heel (walking) or fore-foot (running) to verify that participants actually synchronized their steps to the metronome. Metronome frequency, step frequency and running speed were logged at 10 Hz using a second Arduino microcontroller. The GPS and microcontrollers were mounted to the frame of a lightweight backpack that was worn by the participant during the experiments (total mass: 1.5 kg, figure 2.1).

Experimental protocol

Prior to the actual experiments, participants were familiarized with the equipment, and with synchronizing their steps to a metronome, during a 20-minute practice period. The first ten minutes of the practice period participant's walked/ran to a range of fixed metronome frequencies. The second ten minutes participant's were guided through a range of different speeds to get accustomed to the speed control system. The only instruction given to the participants was to synchronize their steps with the metronome.

Both the walking and running experiment consisted of two parts. In the first part we determined each subject's relationship between prescribed step frequency and speed, by having them walk/run at five different step frequencies for two minutes per frequency. Each step frequency was repeated twice, and the order of frequencies was randomized between participants. To determine the frequency–speed relationship we first calculated

the average speed over the final 30-seconds of each prescribed step frequency. We then fitted a linear polynomial function to these average speeds with prescribed frequency as the independent variable. The slope of this each participant's individual frequency–speed relationship (walking: 0.93 ± 0.09 m/Hz, $R^2 = 0.99 \pm 0.00$; running: 2.07 ± 0.97 m/Hz, $R^2 = 0.80 \pm 0.09$) was then used during the second part of the experiment for the calculation of the individual controller settings.

In the second part of the experiment we tested the performance of the speed control system by guiding participants through a series of target speeds (figure 4.1). Each target speed was maintained for two minutes. Each participant repeated the series twice, once with the speed control system using the default settings, and once with the individual settings. The order of the controller settings was randomized between participants to prevent an order effect.

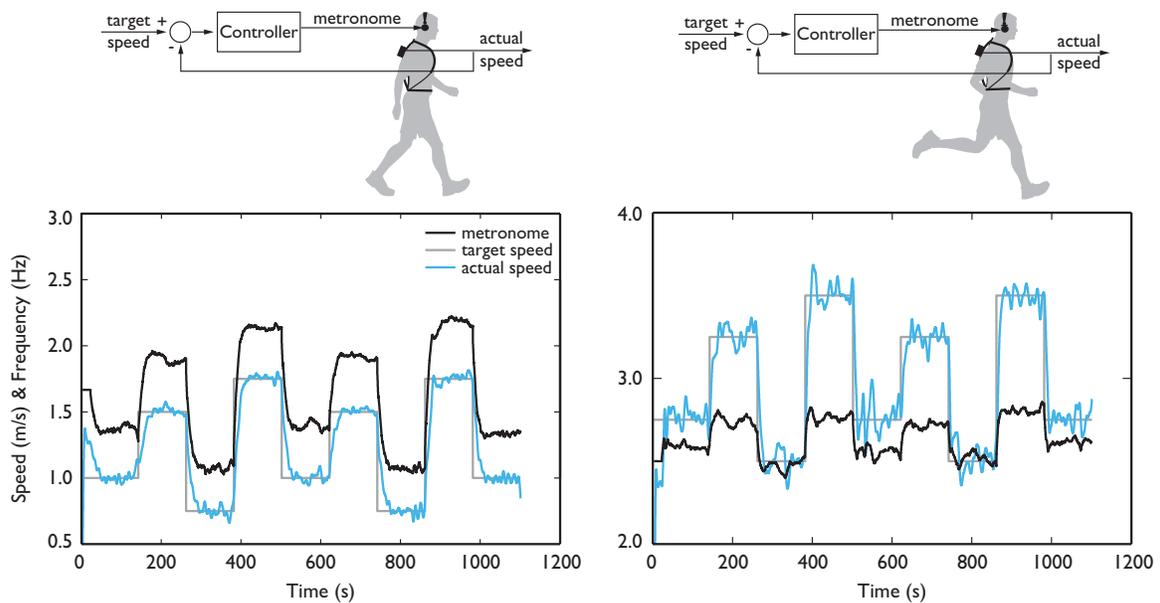


Figure 4.1 Experimental setup and time series data of the experimental protocol
 Subjects walked (left) or ran (right) overground while synchronizing their steps to a metronome. The controller adjusted the metronome frequency based on the measured speed, in order to maintain the actual speed as close as possible to the target speed. The target speed was changed rapidly every 2-minutes, and maintained constant in between these changes.

We used a questionnaire to determine participant's subjective experience when using the speed control system (Appendix C). We asked participants to rate the comfort of using the speed control system, because this was one of our main design criteria. We also asked participants how much change they perceived in both the metronome

frequency and their speed, to determine how participants perceived the constant changes in the metronome frequency introduced by the closed-loop system. Finally, in the running experiment we asked participants how likely they were to use such a speed control system, both in training and during races.

The two parts of the experiment were performed during the same day in the walking experiment, resulting in just under 90 minutes of walking. To prevent fatigue from influencing the results in the running experiment, this experiment was performed over two separate days, resulting in roughly one hour of running per experimental day. To ensure that our findings were not strongly influenced by fatigue, or by the inability of participant's to follow the protocol, we asked participants in the running experiment to rate their perceived exertion following each trial on a Borg scale⁸⁴.

To further demonstrate the effect of varying the controller settings on the system's performance and stability and show the perturbation rejection performance we performed a number of tests with a limited number of subjects (one or two per test). We will discuss the exact nature of each test when presenting the results below.

Results

Accuracy

For walking, the absolute difference between target speed and actual speed during the last minute of each target speed was $0.7 \pm 0.4\%$ when using the default controller settings and $0.7 \pm 0.5\%$ when using the individual settings. For running, this difference was $0.6 \pm 0.4\%$ and $0.4 \pm 0.3\%$ when using the default and individual settings, respectively (figure 4.2 and table 4.1). The variability in speed, calculated as the coefficient of variation over the last minute of each target speed, was $2.8 \pm 1.7\%$ when using the default controller settings and $3.0 \pm 1.8\%$ when using the individual settings for walking. For running the speed variability was $2.3 \pm 0.8\%$ and $2.2 \pm 1.1\%$, respectively. We found no difference in the steady-state (walking: $p=0.19$, running: $p=0.98$, Friedman test) or instantaneous speed error (walking: $p=0.42$, running: $p=0.37$, Friedman test) when using the common or individual gains.

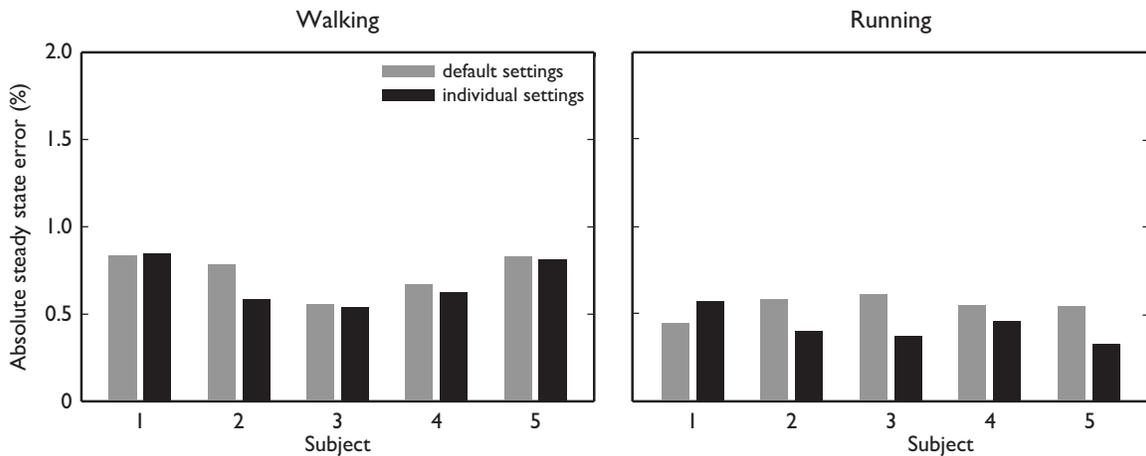


Figure 4.2 Speed error

Average absolute steady state error between the target speed and the actual speed over the last minute of each target speed. Walking results are shown on the left, running results are shown on the right.

	Frequency-speed slope	Steady state error (%)		Response time (s)	
		default	individual	default	individual
Walking					
Subject 1	1.03	0.83 (0.37)	0.84 (0.55)	25.1 (2.70)	23.0 (2.33)
Subject 2	0.91	0.78 (0.53)	0.58 (0.45)	27.6 (5.16)	31.7 (3.12)
Subject 3	0.92	0.55 (0.32)	0.54 (0.39)	28.3 (2.37)	21.0 (2.51)
Subject 4	0.80	0.67 (0.45)	0.62 (0.42)	30.8 (3.50)	18.5 (3.50)
Subject 5	0.97	0.83 (0.34)	0.81 (0.58)	31.7 (3.32)	23.6 (3.48)
Running					
Subject 1	3.25	0.46 (0.31)	0.57 (0.34)	12.1 (5.2)	10.9 (7.8)
Subject 2	2.97	0.59 (0.41)	0.41 (0.32)	12.9 (6.8)	17.0 (7.88)
Subject 3	3.08	0.62 (0.33)	0.38 (0.31)	13.8 (4.3)	11.6 (5.04)
Subject 4	1.58	0.55 (0.44)	0.47 (0.36)	26.2 (9.76)	11.0 (7.08)
Subject 5	0.90	0.55 (0.30)	0.32 (0.25)	44.8 (11.7)	7.81 (4.47)

Table 4.1 Speed control accuracy and responsiveness results

Steady-state error and response time for each subject. The default response times were 21 and 11.4 seconds in walking and running, respectively (Appendix B). The data presented are means, with standard deviations shown between brackets.

Responsiveness

As expected, participants' speed response following changes in target speed was generally faster when using the individual controller settings compared to when using the default settings. To estimate the response time we fitted a single exponential to each individual response (walking: $R^2=0.9\pm0.1$, running: $R^2=0.7\pm0.2$), and multiplied the

resulting time constant by three to determine the response time. During walking, the response time was 28.8 ± 4.2 and 23.7 ± 5.9 seconds when using the default and individual settings, respectively (figure 4.3 and table 4.1, $p=2.3 \times 10^{-5}$, Friedman test). In running, the response time was 20.8 ± 13.9 seconds when using the default settings and 11.7 ± 6.9 seconds when using the individual settings (figure 4.3, $p=0.007$, Friedman test). In running we found a significant relationship between participants' frequency-speed slope and their response time when using the default controller settings ($R^2=0.92$, $p=0.008$, table 4.1), but this relationship disappeared when using the individual controller settings ($R^2=0.38$, $p=0.27$). For walking no relationship was found between participants' frequency-speed slope and their response time when using either the default or individual controller settings.

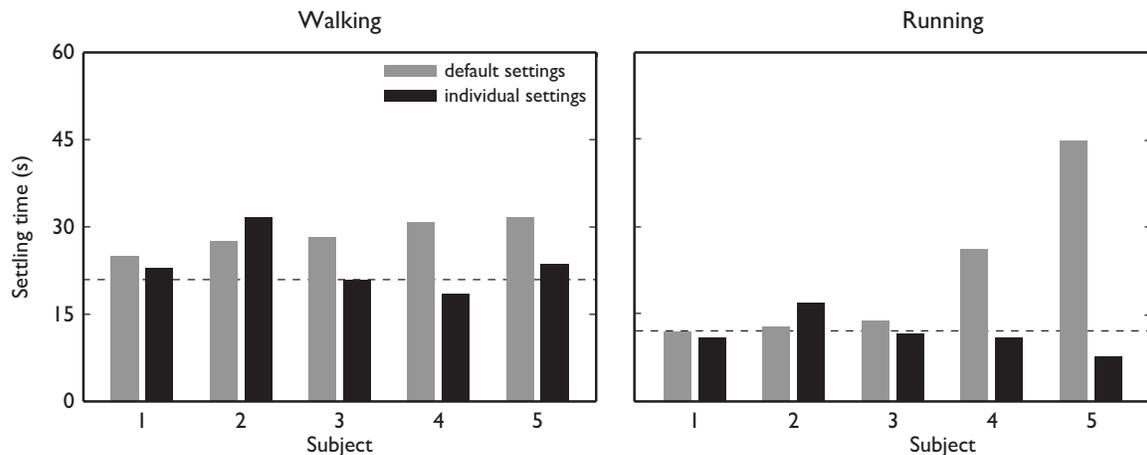


Figure 4.3 Speed response dynamics

Response time of the speed response for both walking (left) and running (right). The dotted line indicates the desired response time used during tuning of the speed control system. Using the default controller settings resulted in quite slow speed responses for some participants, especially during running. When using the individual controller settings, which were determined using the slope of each participant's relationship between frequency and speed, the response time was faster in general, and close to the desired speed response.

Robustness

We found that the speed control system brought participants' speed close to the target speed in 194 out of 198 trials (98%). For all these 194 trials the absolute steady state error between the target speed and the actual speed was below 2%. In the remaining 4 trials, which were the four repetitions of the highest speed for one participant in the running experiment, the required step frequency was too high for the participant to match. Our finding that the speed control system brought participants' actual speed

close to the target speed for all participants indicates that the system's accuracy was robust, at least to the variability within and between participants in this study.

To demonstrate that this robust performance was not a fundamental property of using closed-loop rhythmic pacing to control speed but a result of careful tuning, we tested the individual controller settings determined for one participant on another participant (figure 4.4). The resulting oscillations in speed were well noticeable to the participant, and were perceived as highly uncomfortable. This result demonstrates that the variation between individuals is large enough to result in poor behaviour when the speed control system is not tuned properly.

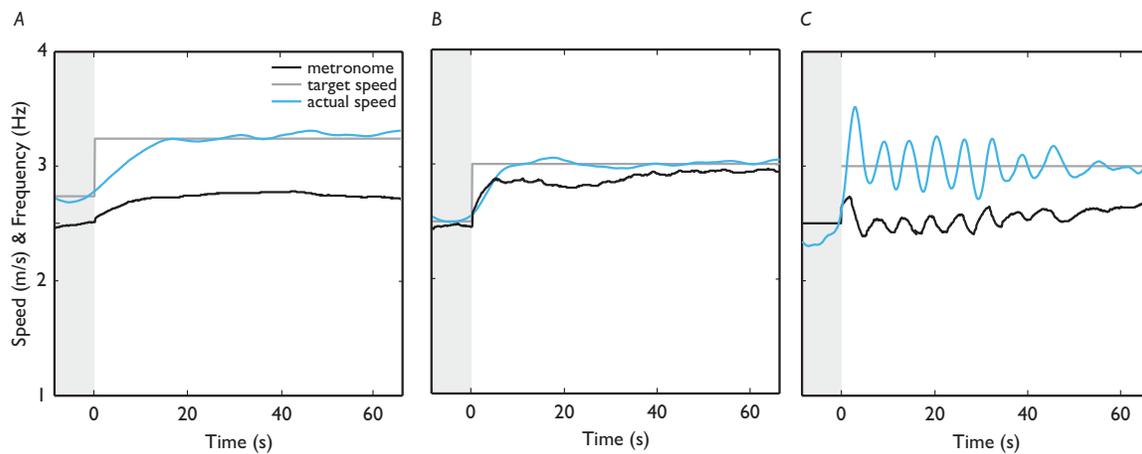


Figure 4.4 Example result for incorrectly tuned control system: oscillation

A) Example speed response for participant 3 when using their individual controller settings. B) Example speed response for participants 5 when using their individual controller settings. C) Speed response of participant 3 when using the individual controller settings determined for participant 5. The latter participant had a much shallower relationship between prescribed step frequency and speed, resulting in higher values for the proportional and integral gain (equations B-3 & B-4). Although these settings worked well for participant 5, when using the same settings for a different participant the speed response showed substantial oscillations. This result demonstrates that the existing variation between individuals is large enough that a control system that works well for one individual might not perform well for another individual. In C the speed control system was turned on at time 0.

Stability

We found that the system resulted in convergence to a constant speed for all participants and all target speeds. Thus, the system was stable.

To demonstrate that it is in fact possible to create behaviour that resembles instability when not tuning the control system carefully, we tested the effect of a very poorly tuned system in one participant (figure 4.5). Although the oscillations are still bounded, this is

an effect of the physiological limits of the participant and not due to the control system—the participant described this run as full-out sprints followed by full-out braking.

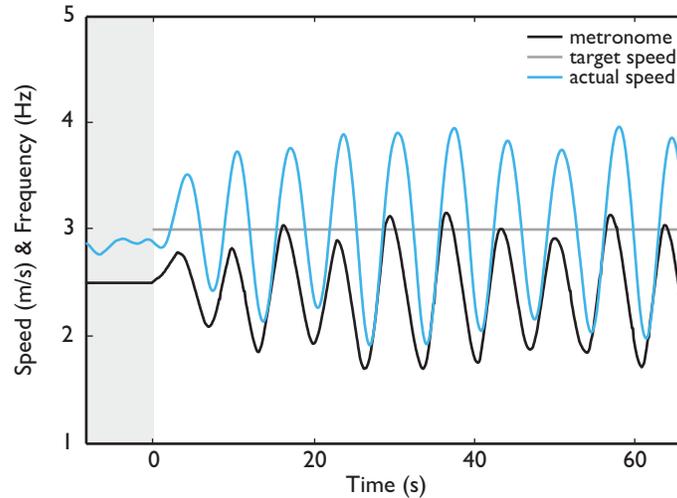


Figure 4.5 Example result for incorrectly tuned control system: instability
Speed response of a single subject using a deliberately mistuned control system (proportional gain = 0, integral gain = 0.5). This result demonstrates that it is possible to create behaviour that resembles instability when the control system is not tuned properly.

Comfort

Between the two experiments, nine out of ten participants rated the use of rhythmic pacing as comfortable (6 participants) or very comfortable (3 participants). The remaining participant perceived the speed control system as uncomfortable. When asked how much change in metronome frequency was perceived, participants responded that they periodically perceived an obvious change, and either no changes (5 participants) or small changes (5 participants) in between these obvious changes. All participants in the running experiment indicated that they were either likely or very likely to use the speed control system during training (including the participant that rated the system as uncomfortable). However, only two participants indicated that they were likely to use the system during a race. Together, these results strongly suggest that the speed control system was comfortable, a metric that is otherwise difficult to quantify.

Discussion

Rhythmic pacing can be used to accurately control overground walking and running speed. By using a closed-loop control system, the average error between the desired

speed and the actual speed was below 1% for all participants. This result was achieved after only 10 minutes of practice with the system, and using a system that was identical for all participants.

The closed-loop system improved the speed control accuracy compared to an open-loop system. For walking, when using the closed-loop control system the average error was $0.7 \pm 0.4\%$ and $2.7 \pm 3.0\%$ when using an open-loop system (Chapter 3). For running, the average error was $0.5 \pm 0.4\%$ when using the closed-loop control system and $3.7 \pm 3.2\%$ when using the open-loop system (Chapter 3). The accuracy improvement achieved here by using a closed-loop control system is not unexpected—although an open-loop system completely depends on an accurate model of the system under control, a closed-loop system can perform well despite an incomplete understanding of the controlled system. It is very unlikely that any model will ever fully grasp the vast complexity of human behaviour, nor the considerable variations between humans. Thus, when the goal is to deliver accurate real-time control of human behaviour, we recommend using a closed-loop system whenever possible.

We found that careful tuning of a closed-loop control system is important to ensure robust performance for a large number of users. The variability between the participants in this study was large enough that a system that worked well for one participant resulted in very poor behaviour for another participant (figure 4.4). This problem is likely not unique to controlling speed, but will probably exist when trying to control other aspects of people's behaviour in real-time as well. So, even though the use of a closed-loop control system reduces the performance effect introduced by variability within and between individuals, our findings demonstrate it is still important to consider this variability to guarantee robust performance for a large number of users.

Although the default control system was very accurate, for some participants the speed response was slower than the desired response. Our findings in the running experiment support the prediction from our simulations that the response time strongly depends on each participant's relationship between prescribed frequency and speed (figure B-10). By adapting the controller settings for each participant using the slope of their frequency–speed relationship we were able to remove this effect, thereby reducing the difference in response time between subjects. Across all subjects, the effect of using the individual controller settings was a decrease in over 40% in response time. Although we

only found a relationship between frequency-speed slope and response time when using the default controller gains in running, it is likely that a similar effect exists in walking. We suspect that the limited range of frequency-speed slopes between our participants prevented us from finding this effect in walking. Thus, we recommend using an adaptive control system when attempting to control gait speed. A fast response not only decreases the time required to converge to a new speed after a change in target speed, but will also decrease the time required to reject any external perturbations.

The closed-loop speed control system developed here delivers accurate control despite the presence of perturbations. Any unmeasured factor that influences the relationship between prescribed frequency and speed can be considered a perturbation. These may include, but are not limited to, changing footwear¹²³, ground surface¹⁰⁹, and hills¹¹⁰. In order to compare the perturbation rejection performance of the closed-loop speed control system to an open-loop system, we performed two single-subject tests. First, we had a subject deliberately change their step length when running using either the open- or closed-loop system. The change in step length directly translated to a change in running speed when using the open-loop system. However, the closed-loop system responded to the change in step length by rapidly changing the prescribed step frequency. As a consequence, the impact on running speed was reduced dramatically (figure 4.6).

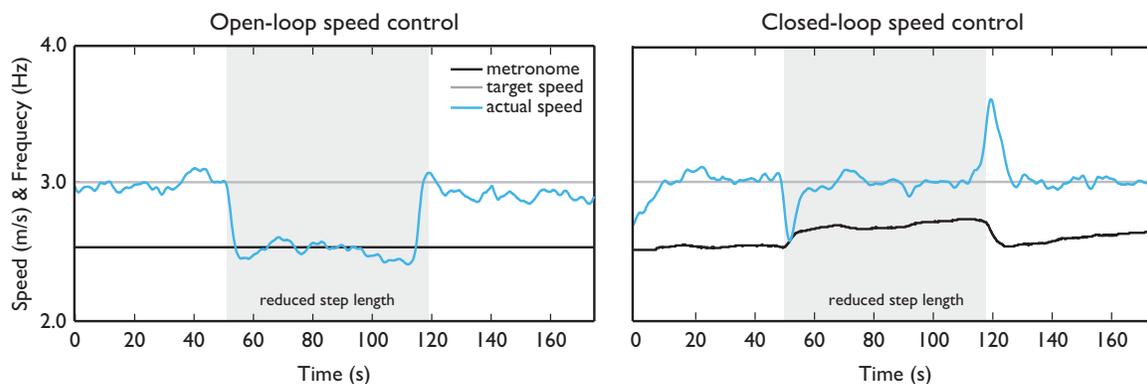


Figure 4.6 Effect step-length perturbation on controlled speed
 Result of sudden changes in step length on running speed when using an open-loop control system (left) and a closed-loop system (right). The start of the grey area indicates a sudden reduction in step length, and the end of the grey area indicates a sudden increase in step length. As expected, the reduction in step length results in a sustained decrease in speed when using an open-loop system. However, when using a closed-loop system, following a reduction in step length the prescribed step frequency is automatically increased to drive the speed back to the target speed. This result demonstrates that the closed-loop control system maintains the runner's speed close to the target speed even in the face of external perturbations.

We found similar results when testing the influence of a hill on running speed when using an open-loop or closed-loop system. As shown in figure 4.7, the speed drops well below the desired speed when running uphill using an open-loop speed control system. However, when using a closed-loop system, the prescribed frequency is increased in order to maintain the runner's speed close to the desired speed. These results show that the closed-loop system indeed accurately controls speed even when external perturbations are present. Note that maintaining a constant speed when encountering a hill is unlikely to be the optimal pacing strategy in every circumstance. All these results demonstrate is the improved ability of the closed-loop speed control system to reject external perturbations compared to an open-loop system.

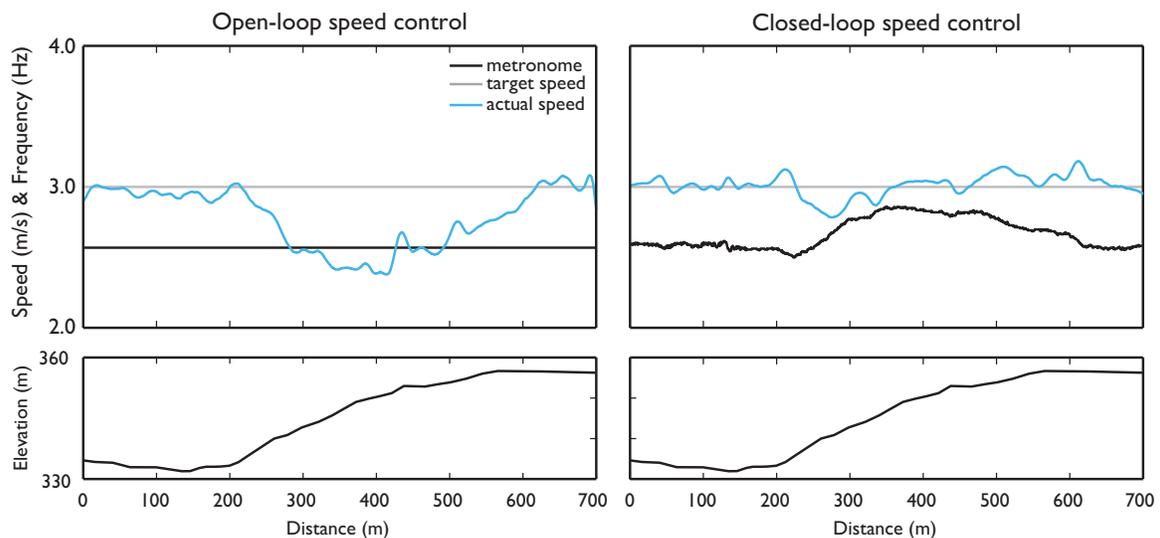


Figure 4.7 Effect of hill perturbation on controlled speed

Result of running uphill on running speed when using an open-loop (left) and closed loop control system (right). The elevation profile of the hill is shown in the bottom plot, and is identical between the two runs. When using the open-loop system, the hill-perturbation results in a sustained decrease in running speed compared to the desired speed. However, when using the closed-loop system, the prescribed frequency is automatically adjusted in order to maintain the runner's speed close to the target speed. This result demonstrates that the closed-loop control system maintains the runner's speed close to the target speed even in the face of external perturbations.

The speed control system developed here can potentially be used to help recreational runners reach their optimal running performance. In a recent study we found that when recreational runner's aim to run a particular speed they make a 4% pacing error on average (Chapter 2). Using a simulation approach we showed that this pacing error has a considerable effect on optimal running performance—our results suggested that due to this error runners perform 5% below their optimum on a 5-kilometer run on average.

Since our speed control system decreased this pacing error to below 1% on average, it could potentially be used to improve running performance in recreational runners. The result of a single-subject pilot experiment testing the effect of the speed control system on running performance is promising. In this pilot experiment we had one participant perform two 4600-meter time trials. For the first trial the participant was instructed to try to run the distance as fast as possible. As can be seen in figure 4.8A, the participant started the run fast and then continuously decreased his speed throughout the run. However, it is generally believed that the optimal pacing strategy for runs of this length is to maintain speed as constant as possible throughout the run^{3,82}, as this strategy reduces the chance of performance reduction due to early exhausting. Hence, we expected that our participant could improve his performance by maintaining a constant speed throughout the run. In the second trial the speed control system was used to help the participant maintain a constant speed (figure 4.8B). To test whether the participant's performance could indeed be increased using such constant speed strategy, the desired speed was set 5% faster than the average speed in the first trial. Although roughly half-way through the run the participant was not able to synchronize his steps to the metronome anymore, his second run was over 3% faster than the first run. Thus, the first test of increasing running performance was promising.

The results of this pilot experiment also highlighted that some changes to the speed control system are desirable before it is used in practice. From the moment the participant was not able to synchronize his steps to the metronome anymore, the speed control system lost its functionality. After the run the subject actually commented that from the moment he was unable to synchronize his steps he perceived the metronome as highly annoying. A number of possible changes could be implemented to prevent this problem. One solution would be to detect when the user is unable to synchronize their steps with the prescribed frequency, and decrease the target speed (temporarily) when this occurs. Another solution would be to use the control system only intermittently, to drive the runner's speed back towards the desired speed whenever it diverges from the desired speed more than some predetermined threshold. It will require future studies to determine the effects of these changes to the system, both in terms of performance and comfort for the user.

One reason why it might not be possible to increase optimal running performance using our speed control system is that it potentially increases the energetic cost required to run at a given speed. As first shown by Bertram & Ruina⁴¹, the energetic cost to walk at a particular speed depends on whether speed, step frequency or step length is constrained. This result was later found for running as well⁴⁰. They showed that when step frequency is constrained, the energetic cost required to walk a particular speed is increased compared to when speed is constrained. Whether using the speed control system developed here indeed increases the energetic cost to run at a given speed remains to be tested.

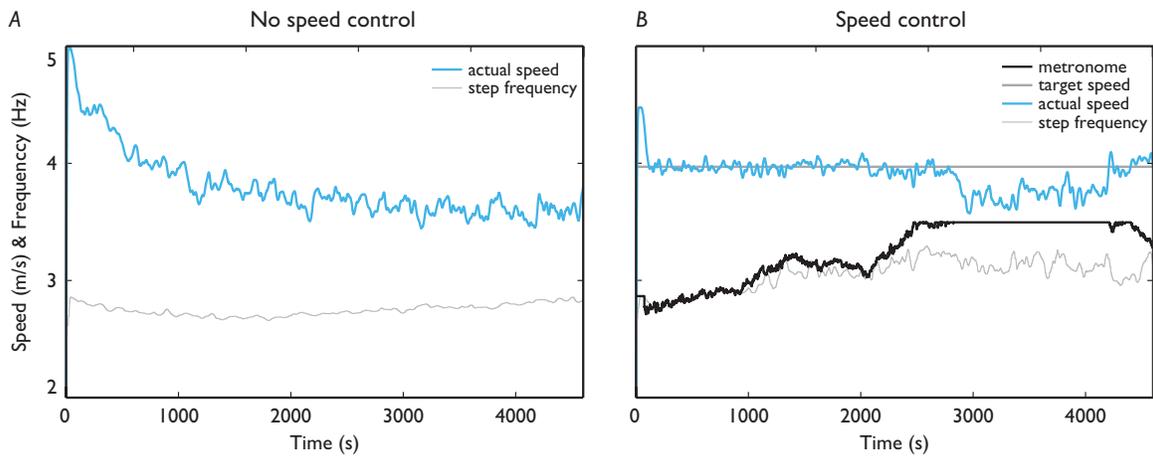


Figure 4.8 Effect of speed control system on maximum running performance

Results of a single-subject experiment testing whether the speed control system can be used to enhance running performance. A) Result of a participant running 4600-meter as fast as possible without the help of any external devices (e.g. watch). It is clear that the participant started fast, and decreased his speed continuously throughout the trial. B) Results of a participant running 4600-meter when using the speed control system. The target speed was set 5% higher than the average speed in A, to test the hypothesis that running performance could be improved by maintaining a constant speed throughout the run. The average speed in B was over 3% faster compared to A. However, from roughly halfway through the trial the participant was unable to synchronize his steps to the prescribed frequency. From this point onwards the speed control system changed from a pacing aid to an annoying beeping. This is a problem that needs to be addressed before the speed control system can be used successfully in practice.

In conclusion, we demonstrated that it is possible to accurately control overground walking and running speed by using auditory rhythmic pacing. Although the functional benefits of this overground pacing system, such as improved running performance or usefulness in rehabilitation practice (Chapter 1) remain to be tested, we believe the current findings are promising.

Chapter 5. From idea to product

Abstract

To make our speed control system available to the public we have translated the system into a smartphone application that can be used during running. This work was done in collaboration with an industry partner specialized in developing smartphone applications and accessories. Translating the system into a commercially available product posed a number of challenges, such as dealing with the lower accuracy and slower dynamics of commercial grade speed sensors. To make the system more enjoyable to use we replaced the metronome with music. To this date the application has been downloaded almost twenty thousands times, and the majority of reviews has been positive.

Introduction

In Chapter 4 my colleagues and I showed that walking and running speed could be controlled with high accuracy using a closed-loop control system. However, the implementation of our system in the experimental setup is far from a product that most people would actually want to use. In this chapter I describe how my colleagues and I have transferred the speed-control system into a product that we believed people would actually enjoy using. We have focussed on developing a training tool for running first, as we believe the benefits of the speed control system in walking will mostly be experienced by certain patient populations during rehabilitation. However, as we have not actually tested the speed control system in these populations yet, it is far too early to consider. Although we could have developed a product that could be used in both walking and running, we decided to focus on only one activity first to simplify the development process. To protect our intellectual property we have applied for a patent (Appendix D), which is currently pending.

Transitioning from research to development to product

When translating the speed control system to a product, an important trade-off existed between the cost and performance of the system. To make our system accessible and enjoyable for a large range of users it needed to conform to the current standards for wearable electronic fitness devices in terms of, for example, size, weight, ease of use and cost. Electronic devices currently used during running typically weigh less than 150g (weight of a mid-size smartphone), and cost less than \$300 (price of a high-end running watch). Clearly, our experimental setup, consisting of a 1.5kg backpack containing over \$2000 in equipment, does not meet these criteria. Furthermore, although using a simple metronome allowed us to test and demonstrate the performance of our system, we believe this is not compatible with a device that most runners would enjoy using.

Because our methodology purely consists of software algorithms, there was no need to develop any new hardware, or to develop a novel form-factor for a wearable fitness device. The minimum requirements for the speed control system to work are present in various existing devices. These minimum requirements are 1) an interface to allow the user to input their desired speed, 2) access to a measure of the users actual speed, 3) sufficient computational power to run the control loop and 4) a method to communicate the prescribed step frequency to the user. All that was required to implement the speed control system was to link existing pieces of hardware in a novel way.

One main challenge when transitioning the speed-control system to an affordable product was to get the system working with existing commercial grade speed-sensors. Using our experimental setup we were able to rapidly bring participants to the desired speed and then keep them there with high accuracy (Chapter 4), but critical to this performance was an expensive, but highly accurate, speed sensor. Commercial-grade speed sensors, such as low-cost GPS sensors or shoe-worn speed sensors, could be expected to have considerably lower accuracy and/or large latencies as a result of heavy filtering¹²⁴. Hence, using an existing, affordable, speed-sensing technology was likely to result in decreased speed-control performance—such as slower convergence onto the desired speed and increased offset between the desired and actual speed—and would likely require significant changes to the control system to deal with the reduced data quality. One alternative would have been to attempt to create a low cost, high accuracy, speed sensor ourselves, but this would have increased the time required to translate our

system into a product. We decided that we would focus on getting the speed-control system out to the public domain first, and perhaps work on developing an improved speed sensing methodology later if this proved desirable.

Another main challenge was to present the speed-control system in a way that people would actually enjoy using. As stated previously, it was hard to imagine that many runners would appreciate running to a metronome for sustained periods of time. Since music is believed to have positive effects on performance and people's enjoyment of exercise (Chapter 1), and many people already listen to music during their exercise, embedding the speed-control system in a musical running experience appeared to be the ideal solution. In fact, results of recent research suggested that the tempo information present in music between the strong beats could actually enhance the ability of users to synchronize their movements to the music¹²⁵. Although this result likely depends on the type of music used, at least it provided confidence that in theory we should be able to reproduce our earlier findings (Chapter 4) using music instead of a metronome.

Based on the requirements for the speed control system the most logical form factor was either a specialized fitness watch or a mobile application for smartphones (*smartphone app*). These devices contain the required user interface to input the desired speed, and the computational power to run the control loop. Furthermore, they usually contain all required hardware to successfully implement the speed-control system, or have the ability to connect to dedicated pieces of hardware required for the speed-control system to work (such as shoe worn speed-sensors or headphones). Finally, these form factors have proven themselves as wearable fitness products that people actually use during their run.

We decided to focus on developing a smartphone application first, as a number of benefits existed compared to implementing our system in a dedicated fitness watch. The first, and perhaps most important benefit, is that implementing our system into a smartphone application allowed us to relatively easily use music instead of a simple metronome. Although smartphones natively have the capabilities to play music, this is generally not true for fitness watches.

The second benefit of developing a smartphone application was that the availability of an open development platform enabled us to leverage the existing hardware without requiring a partnership with the hardware manufacturer. Leveraging an existing piece of hardware allowed us to focus on the novel part of the speed control system—the algorithms—instead of developing the required hardware. As such an open development platform does not exist for existing fitness watches, the only way for us to implement our system into an existing watch would have been to directly collaborate with a watch manufacturer. Although we did pursue this possibility, we were unable to make the required connections at the time. But, we are still interested in this possibility in the future.

Finally, by developing a smartphone application we would be able to offer the system to customers for a relatively low price, as many individuals already own a smartphone. Instead of having to acquire a dedicated piece of hardware, potential users would just need to purchase the software that would allow their device to perform our speed-control methodology. The lower price could decrease the threshold for people to adopt our system in their running regime.

Developing the smartphone application

To develop the smartphone application we collaborated with an industry partner experienced in developing fitness applications for smartphones. The major benefits of this collaboration over developing the application individually were the experience in app development and marketing brought by the industry partner, and the fact that our algorithm's could be built on top of their existing code base. We therefor avoided having to implement many standard features shared between fitness applications, such as connecting to external sensors or data logging, which allowed us to focus on the unique features of our application. The division of responsibilities between the industry partner and us was clear: the industry partner was responsible for the design and development of the user interface and the music implementation, and we were responsible for implementing the algorithms that allowed the music to be adjusted so that it accurately controlled running speed. Basically, our role was to take the sensor information and use this information to output the desired tempo for the currently played music. As described below, we needed to address a number of issues to allow the speed control system to

work properly on a smartphone, using commercially available speed sensors and in everyday running scenarios.

Dealing with low quality speed measurements

Two main speed measurement solutions were available when implementing the speed control system as a smartphone application. Either the relevant sensors internal to the smartphone could be used, or an external shoe-worn speed-sensor that connects wirelessly to the phone. Both solutions have advantages and disadvantages.

Speed measurement using the phones internal sensor

The main advantage of using the phone's internal sensors is that it would not require users to purchase an additional hardware product before they could use the app. The main disadvantage of using the phones internal sensors is their low accuracy. The smartphone we used as a platform for our application contains two different sensors that could in theory be used to determine the users running speed. The first sensor, GPS, provides a position update of the runner roughly once per second. By differentiating this position signal the running speed can be estimated. Although on average the speed estimated from the GPS data is fairly accurate, the low positional accuracy of the phone's GPS results in very noisy estimates of instantaneous running speed (figure 5.1A). In order to use this speed estimate in the speed control system heavily filtering is required, resulting in a considerable lag between the actual speed and the estimated speed. The implication for the speed control system is that it would always be responding to considerably delayed speed information. In order to guarantee good speed control performance, this delay increased the required complexity of the speed control system compared to the system presented in Chapter 4.

The second sensor, an inertial measurement unit (IMU) consisting of a tri-axial accelerometer and gyroscope, provides an acceleration and angular rotation update roughly 100 times per second. Although in theory the accelerometer data could be integrated to determine the current speed (while using the gyroscope signal to determine the required integration constant, see Sabatini et al¹²⁶ for example), the limited range on the smartphone's accelerometer renders this option impossible. The accelerometer in our smartphone of choice registers accelerations between -2 and +2g, but other researchers have found that body fixed accelerometers must be able to register

accelerations within the amplitude range of -12 to +12g to accurately assess daily physical activity¹²⁷. In our testing we indeed found that the accelerations of the upper arm and hand—two common places to wear the smartphone during running—exceed these limits already at low running speeds. This saturation of the accelerometer signals rendered speed estimation by integration of the accelerometer signals impossible and left the GPS as the only directly available option to determine running speed using the phone’s internal sensors (we are currently working on a solution to combine the GPS and IMU information to improve the speed measurement, see future directions).

Speed measurement using an external speed sensor

A dedicated external speed sensor could be expected to deliver improved speed estimates over the phone’s internal GPS. The particular sensor that we considered using was originally developed by Dynastream Innovations Inc. (Canada) and is sold by major fitness companies such as adidas and Garmin. The reason that we considered this particular sensor is because at the time of the app development this was the only speed sensor that connected to a smartphone. In fact, the company that developed the software and hardware required to connect this sensor to a smartphone was our industry partner.

Our testing showed that the speed measurement of the external speed sensor was considerably better than the speed measured using the phone’s GPS (figure 5.1B). When using this external sensor a lag between the actual speed and the measured speed still existed, but this lag was not nearly as large as the lag of the filtered GPS signal. One downside of the external sensor is that in certain instances an offset exists between the measured speed and the actual speed, although this effect could be reduced at a user’s typical running speed by proper calibration of the sensor. Due to the lag present in the external’s speed sensor output considerable changes to the speed control system were also required when using this sensor. However, the expected performance of the speed control system—especially the dynamical performance—was considerably better when using this external sensor compared to the phone’s internal GPS. The main downside of using an external sensor was mentioned earlier—users would have to purchase this sensor (around \$70) before they could use the app.

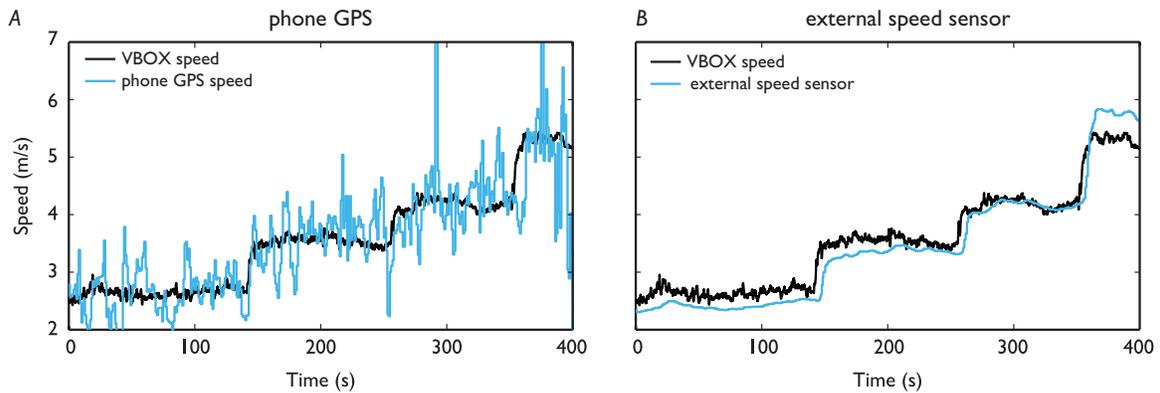


Figure 5.1 Running speed measurements using smartphone

A) Speed measurement using the phone’s internal GPS. The speed as measured with our high-end speed sensor (VBOX) is shown for reference. The speed measurement using the phone’s GPS is fairly accurate on average, but is very noisy when considering instantaneous speed. B) Speed measurement using an external shoe-worn speed sensor. A delay of roughly 6 seconds exists in the speed as provided by the external speed sensor as an effect of filtering. Also, the offset of the measured speed with respect to actual speed grows for slower and higher speeds.

Our solution

We decided to implement the ability to either use the phone’s GPS or an external speed sensor. This would allow users to use the app without purchasing any additional hardware, and to improve the app’s performance by using an external speed sensor if they so desired. Due to our dual implementation, from here onwards *speed sensor* can either refer to the phone’s internal GPS, or the external speed sensor. In order to support both speed sensors, we implemented two different speed control systems tuned for the specifics of each sensor.

Dealing with a real-life run (which is not just running)

Large differences exist between people’s typical running behaviour and their behaviour in an experimental setting. We performed the large majority of the testing in the confined area of an athletics track. In each trial, participants started running on the experimenters command, and only stopped running when the experimenter asked them to do so. In contrast, during everyday running people can be expected to start and stop at any moment during a run. Furthermore, people can be expected to intersperse running with periods of walking, jumping, etc. Ideally, a speed control system will handle all such events without requiring any user action. To illustrate the importance of considering such events when developing a user product, imagine that the user stops running. Since an error exists between the target speed and the actual speed when the user is stopped,

the closed-loop speed control system will increase the prescribed step frequency to reduce this error. The integral control term is especially problematic—as long as the runner is stopped this term will result in a continuous increase in the prescribed frequency. Clearly this behaviour is not desirable. Our general solution to deal with these events is to only update the speed control system whenever the user is actually running. To detect when the user is running, we implemented an algorithm combining the information from the phone's internal accelerometer and the speed sensor used.

Dealing with large perturbations

Although we demonstrated that the speed control system is technically able to maintain the runner's speed close to the target speed even in the face of perturbations such as hills (Chapter 4), it is questionable whether this behaviour is desirable under all circumstances. Different control strategies might be more appropriate, especially when perturbations are large. For example, when a runner encounters a steep incline it is likely that they are physiologically unable to maintain the same speed. And even if they would be able to do so, it is likely that this would not be the optimal running strategy as it might increase the likelihood of early exhaustion (Chapter 2). Ideally a speed control system would effectively handle such situations without requiring any user interaction. One possible solution would be to temporarily turn off the speed control system whenever a large perturbation is detected. Another solution would be to automatically adjust the target speed whenever a large perturbation is detected. Various alternative solutions exist, and although some solutions are less complicated than others, they all share one complexity—the perturbation has to be detected first before an appropriate response is possible. Detecting the perturbation might be relatively straightforward when dealing with hills, but considerably more complex when dealing with other perturbations such as changes in ground surface (e.g. sand) or wind. Instead of directly detecting the various perturbations, our solution was to use the behaviour of the user as a proxy measurement for the presence of any perturbation, and take an appropriate control action accordingly.

Using music instead of a metronome

Controlling running speed using music instead of a metronome improved the user experience but introduced a number of challenges. The basic idea when using music to control running speed is that the playback speed of each song is adjusted to match the

song's tempo to the controller's commanded frequency. The first challenge is that simply changing the playback speed of a song by playing it faster or slower results in a change in the song's pitch (e.g. a song sounds 'higher' when the playback speed is increased). This altered pitch generally decreases the music quality. In order to maintain the song's original pitch while changing the playback speed we used a *time-stretching* algorithm¹²⁸. Such an algorithm works by first subdividing the original signal in short, overlapping, sections. The duration of a song (or equivalently, the playback speed) can be changed without affecting the songs pitch by shifting these short sections relative to each other, and resynthesizing the song using these shifted sections. The main difficulty in the time-stretching algorithm is to successfully handle the discontinuities between the short sections resulting from the time shifting. Instead of implementing our own algorithm, we used an existing software library (a reusable collection of software implementations delivering a well defined behaviour) developed for exactly this purpose (Dirac3, DSP Dimension, Germany).

The second challenge when using music to prescribe step frequency is that the original tempo for each song needs to be known. To detect a songs tempo a *beat-detection* algorithm can be used¹²⁹. Although a number of different algorithms exist, the general idea of all such algorithms is to detect repeating patterns throughout a song (for example by using autocorrelation). Again, instead of implementing our own algorithm we used existing methods. In the current implementation of the application we use two different methods. The application first checks whether the tempo information for each particular song in the users music library is available in a large online music catalogue containing the tempo information for millions of songs (Echo Nest, MA, USA). Whenever a song's tempo information cannot be retrieved from the Echo Nest music catalogue, the app determines the song's tempo using an existing beat-detection software library (SoundTouch, Finland).

A third challenge is to recommend songs that are likely to deliver a positive experience while using the speed-control system. Not every song is equally good at prescribing a runner's step frequency. As a song's tempo can only be changed by a limited amount before the song's quality starts to degrade, or before the user starts to notice the tempo change too clearly, the main requirement for a song to be usable is that the original tempo is close to the runner's cadence. The results of a study by Waterhouse¹³⁰ on

music during cycling suggests that during exercise a song's tempo can be adjusted by as much as ten percent without people noticing a change in the song. From our personal experience, changing a song's tempo by as much as twenty percent is still acceptable. One issue with using music to prescribe step frequency is that people generally do not own a large number of songs with a tempo close to a typical step frequency during running. Based on personal communication with TrainingPeaks¹³¹, owner of a database with running data from thousands of runners, the average step frequency during running is around 165 steps per minute. The tempo distribution of the songs in a number of our beta testers' music libraries is shown in figure 5.2—it is clear that only a limited number of these tester's songs are close to the step frequency during running (and we have no reason to assume these testers have an anomalous music taste). Fortunately, to synchronize their steps to music runners do not necessarily need a beat for every footstep—by synchronizing only every other step with the music, songs with a tempo close to half the step frequency can be used also. This opens up the possibility to roughly twice the number of songs from a user's music library.

A final challenge when using music to prescribe step frequency is that many songs have periods during which their tempo is not clearly distinguishable. As a result, during these periods the music cannot be used to prescribe step frequency. Hence, whenever an error exists between the runner's speed and their desired speed, the playback speed of the music can be changed but this will have no effect on the runner's speed. To prevent the music playback speed from increasing or decreasing too much during such periods, it is necessary to detect the instances that clear tempo information is absent and take an appropriate action accordingly.

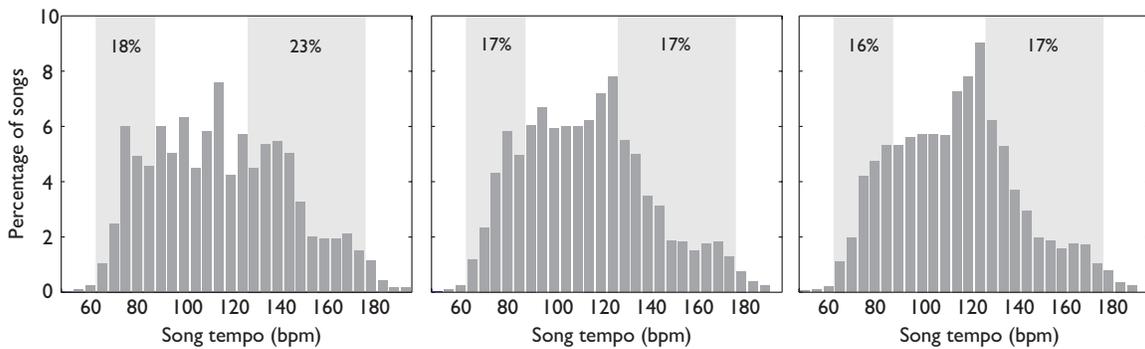


Figure 5.2 Example tempo distribution of songs in tester's music libraries

The data for three representative testers is shown. The grey areas are the tempo ranges that are recommended on default when using the smartphone application. Values inside the grey areas show the percentage of songs in that particular bpm range. The percentage of songs that can be used for controlling running speed is very similar for these three subjects. Users would synchronize each step to the song's beat in the upper range, and synchronize every other step to the song's beat in the lower range.

Testing the application

The testing of the application we performed during the development was quite different than our usual scientific experiments. That is, we did not perform any controlled experiments with randomly selected subjects. Our approach to testing was also different between the early and late development phase.

Early development phase

In the early development phase all testing was performed solely by the development team, and mostly just by myself. As I was responsible for implementing the actual control systems, performing the testing myself allowed me to directly experience the effect of any changes I made. During this phase I would often repeat the exact same running protocol multiple times a day in order to compare the objective data and my subjective experience. This approach allowed me to quickly iterate through changes, which helped to adapt the control systems to the more challenging conditions created by using less accurate speed sensors and encountering real-life running conditions in reasonable time. An important consideration when using this approach was to be careful not to develop a system that only performed well for a subset of runners with similar speed response characteristics as myself. We have shown in Chapter 3 that considerable variability exists in the speed response between individuals, and that this variability has a significant effect on the performance of the speed control system (Chapter 4). Furthermore, since the runner's behaviour is an integral part of the speed control system, another important consideration was to ensure that good performance of the

control system was not solely due to my deep understanding of the system. To verify that the system performed well for a large range of runners, I periodically asked co-developers or friends to use the system. Having others test the system at this stage proved to be highly important—a single run by a naïve user, perhaps with different speed response characteristics than myself, often demonstrated that the performance of the system was not nearly as good as I would have concluded based on my own experience. The lower than expected performance demonstrates a danger present when only the direct responsible developers test their product during the (early) development phase—they might create a product that works great for themselves, but poorly for everyone else.

Late development phase

Once the application's performance was acceptable we recruited a group of 15 *beta testers* to test the performance in a larger group of users. Again, we did not perform any controlled testing. Instead, testers used the application with minimal instructions of how to use it. Testers used their own preferred music and executed their personal running regime. Following each run the data was automatically sent to me for analysis. Often the testers would also email their subjective experience. Based on the tester's data and experience I constantly made slight adjustments to the app's control systems. These updates would install automatically on each tester's phone the next time they used the application. Using a larger group of testers allowed us to verify that the performance of the application was robust against variations between individuals, and even against varying running environments (e.g. flat, hilly, roads, trails, wind) present in different geographical locations as our testers were located all over the world. The benefit of testing the application during actual workouts as opposed to a controlled scientific experiment was that it presented situations that we had not considered. Example time-series data of two typical runs by one of our testers (once when using the footpod, once when using the phone's GPS) are shown in figure 5.3.

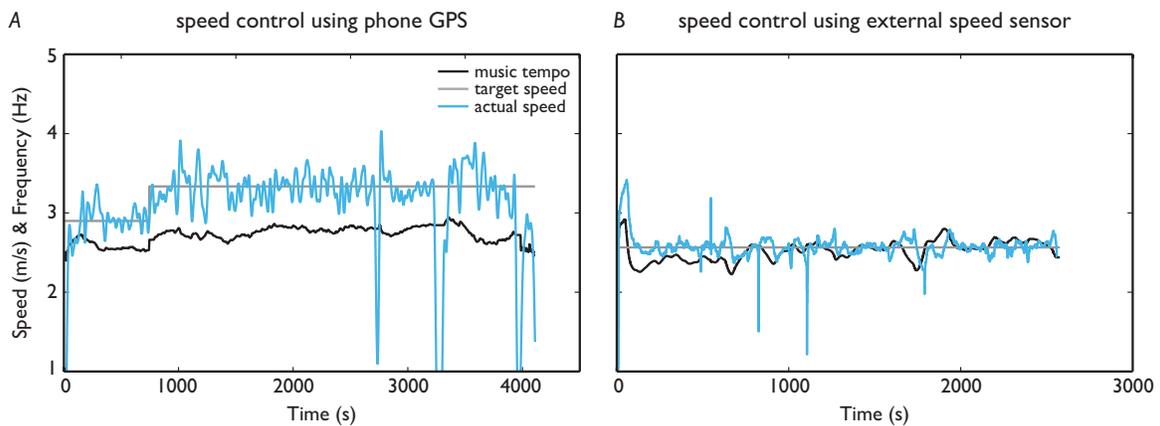


Figure 5.3 Example speed control results

A) Speed control results when using the phone's internal GPS. For clarity the speed estimate from the GPS is filtered using a 20-second moving average. The large drops in measured speed indicate that the tester stopped running. B) Speed control results using the external speed sensor.

Scientific experiment to determine application's performance

We have not yet tested the performance of the application in a controlled, scientific experiment. Consequently, we cannot make any definitive statements about its performance. The main reason we have not yet performed a scientific experiment is limited time and resources, which has forced us to strictly prioritize the work we perform on the application. So far, the priority has been to respond to user feedback. Because we have received minimal negative feedback on the performance of the speed control per se, our focus has been towards improving other aspects of the application, such as the application's user interface. A second reason why we have not yet performed a scientific experiment to test the performance of the smartphone application is because the current implementation is likely not the final implementation. A number of opportunities exist to improve the control systems, but we have yet to implement these. Again, these changes are not a high priority, as users in general seem content with the app's performance.

Current application

Our application has been available in the App Store since late December 2012. Before an App is accepted into the App store it has to be approved based on a review process. Typical reasons for app rejections are instability (i.e. crashes), not conforming to the user interface guidelines, or simply because the app does not do anything useful or

unique¹³². We had no issues getting our app accepted. So far, the app (priced \$4.99) has been downloaded almost 20.000 times by people in over 65 different countries.

Functionality

Music implementation

On first start-up, the app pulls all songs from the native music player present on the phone and analyzes the songs for their tempo. Songs with a tempo relatively close to a typical running cadence are placed in a *recommended* playlist. We use two tempo ranges for these songs (65–90bpm and 130–180bpm). The reason that there are two tempo ranges is that for the low range users synchronize every other step with the beat of the music, whereas for the high range users synchronize each step with the beat. Users can adjust these tempo ranges based on their own preferences. The reason that the pre-set tempo ranges are asymmetric around the typical running tempo is based on our experience that people usually prefer songs better when they are sped up compared to when they are slowed down. If users feel that the tempo of a particular song is not correctly identified, the app provides a tool for users to manually enter the correct tempo for that song simply by tapping the screen in synchrony with the song. To help users identify whether a song will be good during their run, the app has a tool to easily preview a song at the tempo that it will be played at during their run. Users can rate songs at any time (either before, during, or after a run) and filter the music library for songs with particular ratings.

Run modes

Although the description of the application development only described the speed control system, the application actually contains four different *run modes*.

Cadence

In this mode users can select a particular cadence (i.e. step frequency). During their run the app will then play each song at this particular tempo. Basically, this mode is a glorified metronome that uses music instead of beeps. A subset of runners exists that strongly believes that running at a particular tempo results in optimal efficiency and less injuries. Although we do not necessarily agree with these beliefs (especially regarding efficiency), we are nonetheless happy to accommodate these runners. We are surprised by the popularity of this function (23.5% of the recorded runs was using Cadence mode).

Pace

This mode is based on the speed control system developed in this thesis. Users can set their desired pace prior to the run. As long as they synchronize their steps to the music their pace will be close to the target pace. During the run users can easily change their target pace. This mode is the second most popular among the current user base of our app, accounting for 36.4% of the recorded runs.

Heart Rate

This mode is similar to the pace mode, but controls running intensity (quantified using heart rate) instead of running speed. Since speed and heart rate are tightly related during running⁶², heart rate can be controlled using a system similar to our speed-control system. This mode is close to systems such as Yamaha's BODiBEAT, Microsoft's TripleBeat⁵⁹ and Philips IM4Sports⁶⁰ (Chapter 1). In order to use this mode a heart rate strap that connects with the phone is required. Although we had expected that this mode would be popular, in reality it is not used very much yet (only 0.7% of the recorded runs was using heart rate mode). This is likely due to the fact that an external piece of hardware is required to use this mode.

Free Run

In this mode the app synchronizes the music with the users actual step frequency. Instead of the music controlling the runner, the runner controls the music. The phone's accelerometer is used to detect the users step frequency, and the music tempo is changed accordingly. This is similar to other systems such as JoMP⁵⁴, D-Jogger¹³³ and moBeat⁵⁶ (Chapter 1). So far this has been the most popular mode, accounting for 39.3% of the recorded runs.

Media attention and user reviews

Our application has received considerable attention in the media. Printed media that have covered the application include Oprah Magazine, Men's Health, Runner's World and the Globe and Mail. The app has also been covered by some well-respected online media including the New York Times Well Blog, Huffington Post, Gizmodo and All Things D. The media attention was in general very positive. One of the main reasons our app received this much media attention seemed to be the scientific basis underlying its functionality.

The current rating across all App Stores is 3.5 out of 5, based on 122 reviews. Although we have certainly received some negative reviews, the large majority of the reviews have been positive. A large number of negative reviews were triggered by our initial implementation of the music recommendations interface. Instead of giving people freedom to decide what songs they would use, we only accepted certain songs into the app that were within pre-established tempo criteria. As users did not appreciate this behaviour, in our first major update we replaced this by a much more flexible music selection interface with adjustable tempo filters.

Future improvements

Based on user feedback, we plan to further improve our method to select and recommend songs that we believe will provide a positive running experience. Currently, this *recommendation engine* is only using the song's tempo. However, many songs exist with a tempo appropriate to control a runner's step frequency but that are otherwise not suitable for use while running. We are planning to improve the music recommendation engine by using other music qualifiers in the recommendation engine, such as the motivational qualities of each song³⁸.

Another component that we plan to implement in the near future is the ability for users to upload their data to a cloud service. Not only would this allow users to easily keep track of their activities, it would also allow us to determine the performance of the speed control system—and any changes we make to the system—in a large group of individuals. Given that the number of users is getting large, an interesting opportunity is to make changes to the system that only affects the application's behaviour for a portion of the users. Comparing the effects of these changes to the rest of the users would allow us to determine the effect of any changes we introduce.

We believe that it might be possible to improve the speed measurement from the phone's internal sensors by combining the GPS and IMU data. As improved speed measurements would directly translate into improved speed control performance, we plan to integrate such a *sensor fusion* algorithm in the future. My ongoing work on this algorithm is very promising (figure 5.4), but it is not quite ready for implementation in our application. One of the complications is that the phone can be worn in various locations during running, and that the orientation of the phone can change rapidly during a run (for

example when the user is carrying the phone in their hand). Although the GPS data is not affected by changes in location or orientation, this has a major effect on the data provided by the IMU. Hence, in order to augment the GPS-based speed measurement using IMU data, these location and orientation changes will have to be dealt with appropriately.

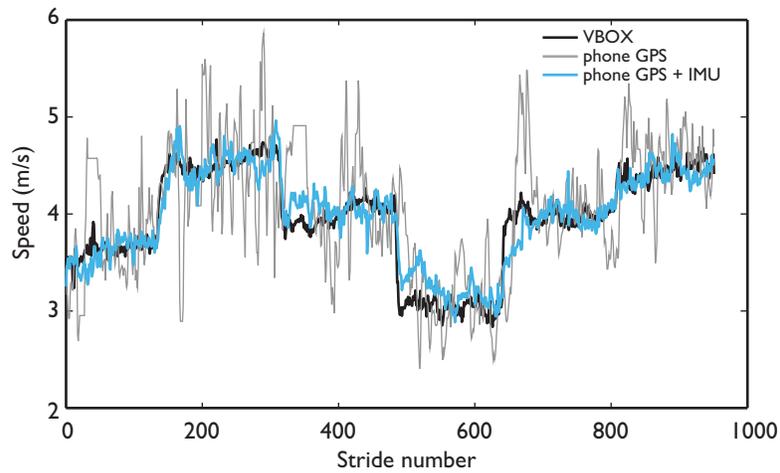


Figure 5.4 Example sensor fusion results

Example results of our sensor fusion algorithm combining the data from the phones GPS and IMU (accelerometer and gyroscope). The data of our high-end speed sensor (VBOX) is shown for reference. It is clear that the sensor fusion algorithm considerably reduces the noise present in the speed measured using the GPS alone.

Chapter 6. Conclusion

The main purpose of this thesis was to explore the possibility to accurately control overground walking and running speed using rhythmic pacing. As stated in the introduction, my hope is that the approach taken in this thesis will serve as a blueprint for the development of other systems for the real-time control of human behaviour. First, my colleagues and I have demonstrated that the optimal performance of recreational runners is reduced by their inability to accurately pace themselves. Second, by studying the dynamics underlying speed selection we have shown that rhythmic pacing provides the required control authority to accurately control overground walking and running speed. Third, we have designed and build a closed-loop overground speed control system. Fourth, we have shown that this system delivers highly accurate speed control during both walking and running, for a range of individuals and in the face of substantial perturbations. And finally, we have developed a training tool based on our speed control system that is now available to the public.

Perhaps the most important lesson from this thesis is that accurate real-time control of human behaviour is possible despite the enormous complexity of human beings. Here, my colleagues and I used the simplest possible dynamical model—a first order system—to describe the entire physiological system responsible for transforming an auditory rhythmic tempo into a preferred speed, including all involved sensors (e.g. ear), control systems (e.g. brain) and actuators (muscles). We then selected and tuned a control system based on this dramatically simplified model. The resemblance between the predicted response based on our simple model, and the actual response when we applied the control system to walking and running humans, was remarkable. Of course, when attempting to control other aspects of human behaviour more complex models, or more complex control systems, might be required. But, I believe that the results presented in this thesis demonstrate that it is worthwhile to investigate other potential applications employing real-time control of human behaviour. Obvious potential applications would be to use similar systems during different workout modes, such as

cycling or swimming. But, I am convinced that there are many other applications waiting to be discovered.

One alternative application, using rhythmic pacing to control heart rate during running, has been described previously⁵⁹⁻⁶¹. However, based on the limited studies on the performance of these technologies its potential was not yet clear. The results presented here, combined with prior work on controlling heart rate during treadmill locomotion^{134,135}, suggest that it should indeed be possible to very accurately control heart rate during overground locomotion. As a proof of concept, I adjusted the speed control system to control heart rate instead. As the results were very promising (see figure 6.1 for example data), we decided to implement the heart rate control system in our smartphone application (Chapter 5).

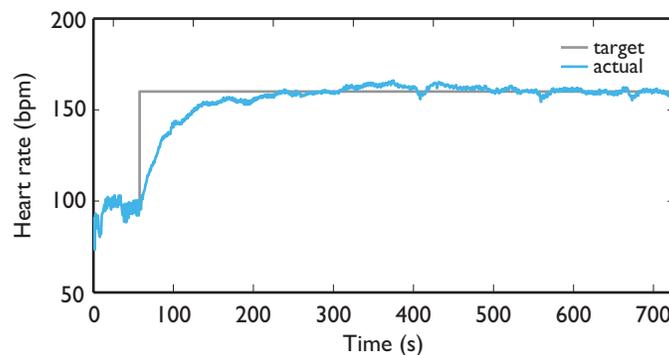


Figure 6.1 Example heart rate control results

The average difference between the target heart rate and the actual heart rate was below 1.5% during steady state. This pilot data suggests that heart rate can indeed be controlled accurately using rhythmic pacing.

In future work I would like to test the influence of using our overground speed control system on the energetic cost of walking and running. It has been shown that the amount of energy required to cover a certain distance at a particular speed will increase while synchronizing steps to a rhythmic stimulus compared to unconstrained walking^{41,68} and running⁴⁰. If our system indeed increases energetic cost over unconstrained locomotion the effectiveness of our speed control system might be limited, especially when the aim is to cover a certain distance as fast as possible. Thus, an improved understanding of the energetic consequence of using our speed control system is desirable.

I would also like to test the performance of the speed control system in patient populations, such as people recovering from stroke or Parkinson's disease. Although my colleagues and I have demonstrated that the speed control system works well during walking, it remains to be tested how this performance transfers to people suffering from such neurological diseases. It is definitely not guaranteed that the speed control system will work well for these individuals as well. Perhaps the mechanisms underlying the selection of preferred speeds are affected, requiring adaptations to the speed control system or even rendering the use of the system impossible. Unfortunately, I have no pilot data that suggests whether the speed control system will actually be useful or not during rehabilitation—this is an open research question for now.

Finally, an exciting avenue that applications such as the smartphone application developed here allow exploring is the results of changes in exercise programs on factors such as workout adherence, injury prevention, and fitness gains. Applications controlling the users behaviour allow researchers to accurately guide participants through exercise programs, without requiring a laboratory environment. As such applications can be easily deployed to very large number of users, these might prove to be useful tools for studying research questions that have been hard to answer due to the large numbers of participants required. For example, these tools might allow the careful determination of optimal running pace and/or mileage for beginner runners to minimize their chance of injuries, perhaps even based on runner's individual characteristics such as age, weight, training history, etc.

References

1. Perry, J., Garrett, M., Gronley, J. K. & Mulroy, S. J. Classification of Walking Handicap in the Stroke Population. *Stroke* **26**, 982–989 (1995).
2. Bijleveld-Uitman, M., Port, I. & Kwakkel, G. Is gait speed or walking distance a better predictor for community walking after stroke? *Journal of Rehabilitation Medicine* **45**, 535–540 (2013).
3. Foster, C., Schrage, M., Snyder, A. C. & Thompson, N. N. Pacing strategy and athletic performance. *Sports Medicine* **17**, 77–85 (1994).
4. Abbiss, C. R. & Laursen, P. B. Describing and understanding pacing strategies during athletic competition. *Sports Medicine* **38**, 239–252 (2008).
5. Green, J. M., Sapp, A. L., Pritchett, R. C. & Bishop, P. A. Pacing accuracy in collegiate and recreational runners. *European Journal of Applied Physiology* **108**, 567–572 (2009).
6. Billat, L. V. Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. *Sports Medicine* **31**, 13–31 (2001).
7. Schmid, A. *et al.* Improvements in speed-based gait classifications are meaningful. *Stroke* **38**, 2096–2100 (2007).
8. Patti, F. *et al.* Effects of Rehabilitation Therapy on Parkinsonians' Disability and Functional Independence. *Neurorehabilitation and Neural Repair* **10**, 223–231 (1996).
9. Ellis, T. *et al.* Efficacy of a physical therapy program in patients with Parkinson's disease: A randomized controlled trial. *Archives of Physical Medicine and Rehabilitation* **86**, 626–632 (2005).
10. Lord, S. E., McPherson, K., McNaughton, H. K., Rochester, L. & Weatherall, M. Community ambulation after stroke: how important and obtainable is it and what measures appear predictive? *Archives of Physical Medicine and Rehabilitation* **85**, 234–239 (2004).
11. Morris, M. E. & Iansek, R. Characteristics of motor disturbance in Parkinson's disease and strategies for movement rehabilitation. *Human Movement Science* **15**, 649–669 (1996).
12. Bohannon, R. W., Andrews, A. W. & Smith, M. B. Rehabilitation Goals of Patients with Hemiplegia. *International Journal of Rehabilitation Research* **11**, 181–183 (1988).

13. Pohl, M., Rockstroh, G., Rückriem, S., Mrass, G. & Mehrholz, J. Immediate effects of speed-dependent treadmill training on gait parameters in early Parkinson's disease. *Archives of Physical Medicine and Rehabilitation* **84**, 1760–1766 (2003).
14. Pohl, M., Mehrholz, J., Ritschel, C. & Ruckriem, S. Speed-Dependent Treadmill Training in Ambulatory Hemiparetic Stroke Patients: A Randomized Controlled Trial. *Stroke* **33**, 553–558 (2002).
15. Cakit, B. D., Saracoglu, M., Genc, H., Erdem, H. R. & Inan, L. The effects of incremental speed-dependent treadmill training on postural instability and fear of falling in Parkinson's disease. *Clinical Rehabilitation* **21**, 698–705 (2007).
16. Herman, T., Giladi, N., Gruendlinger, L. & Hausdorff, J. M. Six weeks of intensive treadmill training improves gait and quality of life in patients with Parkinson's disease: a pilot study. *Archives of Physical Medicine and Rehabilitation* **88**, 1154–1158 (2007).
17. Reisman, D. S., Wityk, R., Silver, K. & Bastian, A. J. Split-belt treadmill adaptation transfers to overground walking in persons poststroke. *Neurorehabilitation and Neural Repair* **23**, 735–744 (2009).
18. Willoughby, K. L., Dodd, K. J. & Shields, N. A systematic review of the effectiveness of treadmill training for children with cerebral palsy. *Disability and Rehabilitation* **31**, 1971–1979 (2009).
19. Newman, M. A. *et al.* Can aerobic treadmill training reduce the effort of walking and fatigue in people with multiple sclerosis: a pilot study. *Multiple Sclerosis* **13**, 113–119 (2007).
20. Gioia, T. *Work songs*. (Duke University Press, 2006).
21. Demos, A. P., Chaffin, R., Begosh, K. T., Daniels, J. R. & Marsh, K. L. Rocking to the beat: effects of music and partner's movements on spontaneous interpersonal coordination. *Journal of Experimental Psychology: General* **141**, 49–53 (2012).
22. Phillips-Silver, J. Feeling the beat: movement influences infant rhythm perception. *Science* **308**, 1430–1430 (2005).
23. Zentner, M. & Eerola, T. Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences* **107**, 5768–5773 (2010).
24. Drake, C. Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics* **53**, 25–33 (1993).
25. McKinney, C. H., Tims, F. C., Kumar, A. M. & Kumar, M. The effect of selected classical music and spontaneous imagery on plasma β -endorphin. *Journal of Behavioral Medicine* **20**, 85–99 (1997).
26. Dunbar, R. I. M., Kaskatis, K., MacDonald, I. & Barra, V. Performance of music elevates pain threshold and positive affect: implications for the evolutionary function of music. *Evolutionary Psychology* **10**, 688–702 (2012).
27. Cohen, E. E. A., Ejsmond-Frey, R., Knight, N. & Dunbar, R. I. M. Rowers' high: behavioural synchrony is correlated with elevated pain thresholds. *Biology Letters* **6**, 106–108 (2010).

28. Zatorre, R. J., Chen, J. L. & Penhune, V. B. When the brain plays music: auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience* **8**, 547–558 (2007).
29. Blood, A. J. & Zatorre, R. J. Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proc. Natl. Acad. Sci. U.S.A.* **98**, 11818–11823 (2001).
30. Koelsch, S. Towards a neural basis of music-evoked emotions. *Trends in Cognitive Sciences* **14**, 131–137 (2010).
31. Patel, A. D. Music, biological evolution, and the brain. *Emerging disciplines* 91–144 (2010).
32. Karageorghis, C. I. & Priest, D.-L. Music in the exercise domain: a review and synthesis (Part I). *International Review of Sport and Exercise Psychology* **5**, 44–66 (2012).
33. Karageorghis, C. I. & Priest, D.-L. Music in the exercise domain: a review and synthesis (Part II). *International Review of Sport and Exercise Psychology* **5**, 67–84 (2012).
34. Hayakawa, Y., Miki, H., Takada, K. & Tanaka, K. Effects of music on mood during bench stepping exercise. *Perceptual and Motor Skills* **90**, 307–314 (2000).
35. Simpson, S. D. & Karageorghis, C. I. The effects of synchronous music on 400-m sprint performance. *Journal of Sports Sciences* **24**, 1095–1102 (2006).
36. Karageorghis, C. I. *et al.* Psychophysical and ergogenic effects of synchronous music during treadmill walking. *Journal of Sport & Exercise Psychology* **31**, 18–36 (2009).
37. Terry, P. C., Karageorghis, C. I., Saha, A. M. & D’Auria, S. Effects of synchronous music on treadmill running among elite triathletes. *Journal of Science and Medicine in Sport* **15**, 52–57 (2012).
38. Karageorghis, C. I., Priest, D.-L., Terry, P. C., Chatzisarantis, N. L. D. & Lane, A. M. Redesign and initial validation of an instrument to assess the motivational qualities of music in exercise: The Brunel Music Rating Inventory-2. *Journal of Sports Sciences* **24**, 899–909 (2006).
39. Bood, R. J., Nijssen, M., van der Kamp, J. & Roerdink, M. The power of auditory-motor synchronization in sports: enhancing running performance by coupling cadence with the right beats. *PLoS ONE* **8**, e70758 (2013).
40. Gutmann, A. K., Jacobi, B., Butcher, M. T. & Bertram, J. Constrained optimization in human running. *Journal of Experimental Biology* **209**, 622–632 (2006).
41. Bertram, J. & Ruina, A. Multiple walking speed–frequency relations are predicted by constrained optimization. *Journal of Theoretical Biology* **209**, 445–453 (2001).
42. Thaut, M. H., McIntosh, G. C., Prassas, S. G. & Rice, R. R. Effect of rhythmic auditory cuing on temporal stride parameters and EMG. Patterns in hemiparetic gait of stroke patients. *Neurorehabilitation and Neural Repair* **7**, 9–16 (1993).

43. Prassas, S., Thaut, M., McIntosh, G. & Rice, R. Effect of auditory rhythmic cuing on gait kinematic parameters of stroke patients. *Gait & Posture* **6**, 218–223 (1997).
44. Thaut, M. H., McIntosh, G. C. & Rice, R. R. Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation. *Journal of Neurological Sciences* **151**, 207–212 (1997).
45. Thaut, M. H. *et al.* Rhythmic auditory stimulation in gait training for Parkinson's disease patients. *Mov Disord.* **11**, 193–200 (1996).
46. McIntosh, G. C., Brown, S. H., Rice, R. R. & Thaut, M. H. Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. *Journal of Neurology, Neurosurgery & Psychiatry* **62**, 22–26 (1997).
47. Willems, A. M. *et al.* The use of rhythmic auditory cues to influence gait in patients with Parkinson's disease, the differential effect for freezers and non-freezers, an explorative study. *Disability and Rehabilitation* **28**, 721–728 (2006).
48. Howe, T., Lovgreen, B., Cody, F., Ashton, V. & Oldham, J. Auditory cues can modify the gait of persons with early-stage Parkinson's disease: a method for enhancing parkinsonian walking performance? *Clinical Rehabilitation* **17**, 363–367 (2003).
49. Jahanshahi, M. *et al.* Self-initiated versus externally triggered movements I. An investigation using measurement of regional cerebral blood flow with PET and movement-related potentials in normal and Parkinson's disease subjects. *Brain* **118**, 913–933 (1995).
50. Cunnington, R., Windischberger, C., Deecke, L. & Moser, E. The preparation and execution of self-initiated and externally-triggered movement: a study of event-related fMRI. *NeuroImage* **15**, 373–385 (2002).
51. Peper, C. L. E., Oorthuizen, J. K. & Roerdink, M. Gait & Posture. *Gait & Posture* **36**, 378–382 (2012).
52. de Bruin, N. *et al.* Walking with Music Is a Safe and Viable Tool for Gait Training in Parkinson's Disease: The Effect of a 13-Week Feasibility Study on Single and Dual Task Walking. *Parkinson's Disease* **2010**, 1–9 (2010).
53. Nieuwboer, A. *et al.* Cueing training in the home improves gait-related mobility in Parkinson's disease: the RESCUE trial. *Journal of Neurology, Neurosurgery & Psychiatry* **78**, 134–140 (2007).
54. Liu, N.-H. & Kung, H.-Y. JoMP: a mobile music player agent for joggers based on user interest and pace. *Consumer Electronics, IEEE Transactions on* **55**, 2225–2233 (2009).
55. Moens, B., van Noorden, L. & Leman, M. D-Jogger: Syncing music with walking. *Proceedings of SMC Conference* 451–456 (2010).
56. Vlist, B., Bartneck, C. & Mäueler, S. moBeat: using interactive music to guide and motivate users during aerobic exercising. *Applied Psychophysiological Biofeedback* **36**, 135–145 (2011).

57. Marschollek, M. *et al.* A performance comparison of accelerometry-based step detection algorithms on a large, non-laboratory sample of healthy and mobility-impaired persons. *30th Annual International IEEE EMBS Conference* **2008**, 1319–1322 (2008).
58. Laroche, J. Autocorrelation method for high-quality time/pitch-scaling. *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics* 131–134 (1993).
59. de Oliveira, R. & Oliver, N. TripleBeat: enhancing exercise performance with persuasion. *10th International Conference on Human Computer Interaction with Mobile Devices and Services* 255–264 (2008).
60. Wijnalda, G., Pauws, S., Vignoli, F. & Stuckenschmidt, H. A personalized music system for motivation in sport performance. *Pervasive Computing, IEEE* **4**, 26–32 (2005).
61. Oliver, N. & Kreger-Stickles, L. Enhancing exercise performance through real-time physiological monitoring and music: a user study. *Pervasive Health Conference and Workshops* 1–10 (2006).
62. Hermansen, L. & Saltin, B. Oxygen uptake during maximal treadmill and bicycle exercise. *Journal of Applied Physiology* **26**, 31–37 (1969).
63. Miyake, Y. Interpersonal synchronization of body motion and the Walk-Mate walking support robot. *IEEE Transactions on Robotics* **25**, 638–644 (2009).
64. van Ulzen, N. R., Lamoth, C. J. C., Daffertshofer, A., Semin, G. R. & Beek, P. J. Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side. *Neuroscience Letters* **432**, 88–93 (2008).
65. Hove, M. J., Suzuki, K., Uchitomi, H., Orimo, S. & Miyake, Y. Interactive rhythmic auditory stimulation reinstates natural 1/f timing in gait of Parkinson's patients. *PLoS ONE* **7**, e32600 (2012).
66. Takeshi Muto, B. H. J. H. Y. M. E. P. Interactive gait training device 'Walk-Mate' for hemiparetic stroke rehabilitation. *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems* 2268–2274 (2007).
67. Heeren, A. *et al.* Step by step: A proof of concept study of C-Mill gait adaptability training in the chronic phase after stroke. *Journal of Rehabilitation Medicine* **45**, 616–622 (2013).
68. Bertram, J. E. A. Constrained optimization in human walking: cost minimization and gait plasticity. *Journal of Experimental Biology* **208**, 979–991 (2005).
69. Snaterse, M., Ton, R., Kuo, A. D. & Donelan, J. M. Distinct fast and slow processes contribute to the selection of preferred step frequency during human walking. *Journal of Applied Physiology* **110**, 1682–1690 (2011).
70. Snyder, K. L., Snaterse, M. & Donelan, J. M. Running perturbations reveal general strategies for step frequency selection. *Journal of Applied Physiology* **112**, 1239–1247 (2012).
71. O'Connor, S. M. & Donelan, J. M. Fast visual prediction and slow optimization of preferred walking speed. *Journal of Neurophysiology* **107**, 2549–2559 (2012).

72. Astrom, K. J. & Murray, R. M. *Feedback Systems*. (Princeton University Press, 2010).
73. Hopkins, W. G. & Hewson, D. J. Variability of competitive performance of distance runners. *Medicine & Science in Sports & Exercise* **33**, 1588–1592 (2001).
74. Wilkie, D. R. Man as a source of mechanical power. *Ergonomics* **3**, 1–8 (1960).
75. Tucker, R., Lambert, M. I. & Noakes, T. D. An analysis of pacing strategies during men's world-record performances in track athletics. *International journal of sports physiology and performance* **1**, 233–245 (2006).
76. Tucker, R. & Noakes, T. D. The physiological regulation of pacing strategy during exercise: a critical review. *British Journal of Sports Medicine* **43**, e1–e1 (2009).
77. Coats, E. M. *et al.* Intensity-dependent tolerance to exercise after attaining VO₂ max in humans. *Journal of Applied Physiology* **95**, 483–490 (2003).
78. Fukuba, Y. & Whipp, B. J. A metabolic limit on the ability to make up for lost time in endurance events. *Journal of Applied Physiology* **87**, 853–861 (1999).
79. Liedl, M. A., Swain, D. P. & Branch, J. D. Physiological effects of constant versus variable power during endurance cycling. *Medicine & Science in Sports & Exercise* **31**, 1472 (1999).
80. Lepers, R., Theurel, J., Hausswirth, C. & Bernard, T. Neuromuscular fatigue following constant versus variable-intensity endurance cycling in triathletes. *Journal of Science and Medicine in Sport* **11**, 381–389 (2008).
81. Gosztyla, A. E., Edwards, D. G., Quinn, T. J. & Kenefick, R. W. The impact of different pacing strategies on five-kilometer running time trial performance. *Journal of Strength and Conditioning Research* **20**, 882–886 (2006).
82. Thiel, C., Foster, C., Banzer, W. & De Koning, J. Pacing in Olympic track races: competitive tactics versus best performance strategy. *Journal of Sports Sciences* **30**, 1107–1115 (2012).
83. IAAF. *Track and Field Facilities Manual*. 1–140 (Editions EGC, 2008).
84. Borg, G. A. Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise* **14**, 377–381 (1982).
85. McClave, J. T. & Sincich, T. *Statistics*. (Prentice Hall, 2009).
86. Press, W. H. *Numerical Recipes*. (Cambridge University Press, 2007).
87. Hughson, R. L., Orok, C. J. & Staudt, L. E. A high velocity treadmill running test to assess endurance running potential. *International Journal of Sports Medicine* **5**, 23–25 (1984).
88. Kranenburg, K. J. & Smith, D. J. Comparison of critical speed determined from track running and treadmill tests in elite runners. *Medicine & Science in Sports & Exercise* **28**, 614–618 (1996).
89. Fukuba, Y. *et al.* The curvature constant parameter of the power-duration curve for varied-power exercise. *Medicine & Science in Sports & Exercise* **35**, 1413–1418 (2003).

90. Pepper, M. L., Housh, T. J. & Johnson, G. O. The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. *International Journal of Sports Medicine* **13**, 121–124 (1992).
91. Housh, T. J., Johnson, G. O., McDowell, S. L., Housh, D. J. & Pepper, M. Physiological responses at the fatigue threshold. *International Journal of Sports Medicine* **12**, 305–308 (1991).
92. Florence, S. & Weir, J. P. Relationship of critical velocity to marathon running performance. *European Journal of Applied Physiology* **75**, 274–278 (1997).
93. Morton, R. H. & Hodgson, D. J. The relationship between power output and endurance: a brief review. *European Journal of Applied Physiology* **73**, 491–502 (1996).
94. Miura, A., Sato, H., Sato, H., Hipp, B. J. W. & Fukuba, Y. The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics* **43**, 133–141 (2000).
95. Hill, D. W., Poole, D. C. & Smith, J. C. The Relationship Between Power and the Time to Achieve VO₂Max. *Medicine & Science in Sports & Exercise* **34**, 709–714 (2002).
96. Whipp, B. J., Ward, S. A., Lamarra, N., Davis, J. A. & Wasserman, K. Parameters of ventilatory and gas exchange dynamics during exercise. *Journal of Applied Physiology* **52**, 1506–1513 (1982).
97. Poole, D. C., Ward, S. A., Gardner, G. W. & Whipp, B. J. Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics* **31**, 1265–1279 (1988).
98. Gaesser, G. A. & Wilson, L. A. Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *International Journal of Sports Medicine* **9**, 417–421 (1988).
99. Details | Running USA. *Running USA* at <<http://www.runningusa.org/statistics>>
100. Bartlett, M. S. & Kendall, D. G. The statistical analysis of variance-heterogeneity and the logarithmic transformation. *Supplement to the Journal of the Royal Statistical Society* **8**, 128–138 (1946).
101. Susan G Komen 2013 Race Results. *albanyrunningexchange.org* at <<http://www.albanyrunningexchange.org/results/search.php?ID=3067>>
102. Nicholson, R. M. & Sleivert, G. G. Indices of lactate threshold and their relationship with 10-km running velocity. *Medicine & Science in Sports & Exercise* **33**, 339–342 (2001).
103. Åstrand, P.-O., Rodahl, K., Dahl, H. A. & Stromme, S. B. *Textbook of Work Physiology*. (Human Kinetics, 2003).
104. Diedrich, F. J. & Warren, W. H. Why change gaits? Dynamics of the walk-run transition. *Journal of Experimental Psychology: Human Perception and Performance* **21**, 183–202 (1995).
105. Alexander, R. M. Optimization and Gaits in the Locomotion of Vertebrates. *Physiological Reviews* **69**, 1199–1227 (1989).

106. Elftman, H. Biomechanics of Muscle: with particular application to studies of gait. *Journal of bone & joint surgery* **48**, 363–377 (1966).
107. Hoyt, D. F. & Taylor, C. R. Gait and the energetics of locomotion in horses. *Nature* (1981).
108. Bertram, J., Prebeau-Menezes, L. & Szarko, M. J. Gait characteristics over the course of a race in recreational marathon competitors. *Research Quarterly for Exercise and Sport* **84**, 6–15 (2013).
109. Pinnington, H. C., Lloyd, D. G., Besier, T. F. & Dawson, B. Kinematic and electromyography analysis of submaximal differences running on a firm surface compared with soft, dry sand. *European Journal of Applied Physiology* **94**, 242–253 (2005).
110. Townshend, A. D., Worringham, C. J. & Stewart, I. B. Spontaneous Pacing during Overground Hill Running. *Medicine & Science in Sports & Exercise* **42**, 160–169 (2010).
111. Skogestad, S. Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control* **13**, 291–309 (2003).
112. De Groen, P. & De Moor, B. The fit of a sum of exponentials to noisy data. *Journal of Computational and Applied Mathematics* **20**, 175–187 (1987).
113. Moré, J. J. The Levenberg-Marquardt algorithm: implementation and theory. *Numerical Analysis* 105–116 (1978).
114. Ferretti, G., Maffezzoni, C. & Scattolini, R. On the identifiability of the time delay with least-squares methods. *Automatica* **32**, 449–453 (1996).
115. Müller, T. *et al.* Estimation of delay times in biological systems. *Annals of Biomedical Engineering* **31**, 1423–1439
116. Efron, B. & Tibshirani, R. *An introduction to the bootstrap*. (Chapman & Hall, 1993).
117. Large, E., Fink, P. & Kelso, S. Tracking simple and complex sequences. *Psychological Research* **66**, 3–17 (2002).
118. Burke, C. Marching to Vietnam. *Journal of American Folklore* 424–441 (1989).
119. Styns, F., van Noorden, L., Moelants, D. & Leman, M. Walking on music. *Human Movement Science* **26**, 769–785 (2007).
120. Astrom, K. J. & Hagglund, T. *PID Controllers: Theory, Design and Tuning*. 1–354 (Instrument Society Of America, 1995).
121. Gallagher, N., Jr & Wise, G. A theoretical analysis of the properties of median filters. *Acoustics, Speech and Signal Processing, IEEE Transactions on* **29**, 1136–1141 (1981).
122. Stewart, R. R. Median filtering: Review and a new f/k analogue design. *Journal of the Canadian Society of Exploration Geophysicists* **1**, 54–63 (1985).
123. De Wit, B., De Clercq, D. & Aerts, P. Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics* **33**, 269–278 (2000).

124. Tan, H., Wilson, A. M. & Lowe, J. Measurement of stride parameters using a wearable GPS and inertial measurement unit. *Journal of Biomechanics* **41**, 1398–1406 (2008).
125. Thaut, M. H., Rathbun, J. A. & Miller, R. A. Music versus Metronome Timekeeper in a Rhythmic Motor Task. *International Journal of Arts Medicine* **5**, 4–12 (1997).
126. Sabatini, A. M., Martelloni, C., Scapellato, S. & Cavallo, F. Assessment of walking features from foot inertial sensing. *IEEE Transactions on Biomedical Engineering* **52**, 486–494 (2005).
127. Bouten, C. V., Koekkoek, K. T., Verduin, M., Kodde, R. & Janssen, J. D. A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity. *IEEE Transactions on Biomedical Engineering* **44**, 136–147 (1997).
128. *dspdimension.com*. at <<http://www.dspdimension.com>>
129. McKinney, M. F., Moelants, D., Davies, M. E. P. & Klapuri, A. Evaluation of audio beat tracking and music tempo extraction algorithms. *Journal of New Music Research* **36**, 1–16 (2007).
130. Waterhouse, J., Hudson, P. & Edwards, B. Effects of music tempo upon submaximal cycling performance. *Scandinavian Journal of Medicine & Science in Sports* **20**, 662–669 (2009).
131. *trainingpeaks.com*. at <<http://www.trainingpeaks.com>>
132. Apple Inc. App Store Review Guidelines - App Store Resource Center. *developer.apple.com* at <<https://developer.apple.com/appstore/resources/approval/guidelines.html>>
133. Moens, B., van Noorden, L. & Leman, M. D-Jogger: a multimodal music interface for music selection based on user step frequency. *Proceedings of Haptic Audio Interface Design* 1–2 (2010).
134. Cheng, T. M., Savkin, A. V., Su, S. W., Celler, B. G. & Wang, L. A robust control design for heart rate tracking during exercise. *30th Annual International IEEE EMBS Conference* **2008**, 2785–2788 (2008).
135. Su, S. W., Lu Wang, Celler, B. G., Savkin, A. V. & Ying Guo. Identification and control for heart rate regulation during treadmill exercise. *IEEE Transactions on Biomedical Engineering* **54**, 1238–1246 (2007).
136. Grimble, M. J. *Robust industrial control: optimal design approach for polynomial systems*. (Prentice-Hall, Inc., 1994).
137. Astrom, K. J. & Hägglund, T. The future of PID control. *Control engineering practice* **9**, 1163–1175 (2001).
138. Panda, R. C., Yu, C.-C. & Huang, H.-P. PID tuning rules for SOPDT systems: review and some new results. *ISA Trans* **43**, 283–295 (2004).
139. Brackstone, M. & McDonald, M. Car-following: a historical review. *Transportation Research Part F: Traffic Psychology and Behaviour* **2**, 181–196 (1999).

140. Rivera, D. E., Morari, M. & Skogestad, S. Internal model control: PID controller design. *Industrial & engineering chemistry process design and development* **25**, 252–265 (1986).

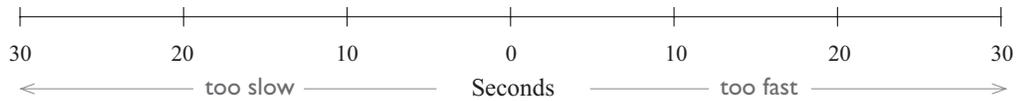
Appendix A.

Running self-pacing questionnaire

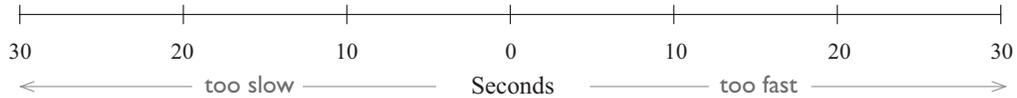
When instructed to run at a constant speed, how did you pace yourself?

When instructed to run 10% faster or slower, how did you pace yourself?

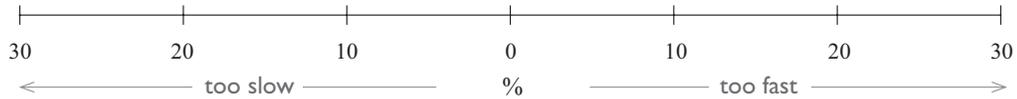
How much do you think your average lap time differed from the instructed time when asked to run slower?



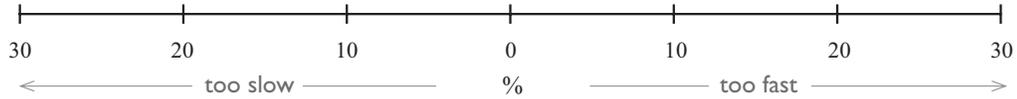
How much do you think your average lap time differed from the instructed time when asked to run faster?



How much do you think your average speed differed from the instructed speed when asked to run slower?



How much do you think your average speed differed from the instructed speed when asked to run faster?



How do you normally pace yourself during your training runs?

How do you normally pace yourself during your races? *(leave this blank if you don't race)*

Appendix B.

Closed-loop speed control system design

Before discussing the details of the control system design we will define some terms (figure B-1). We provide both general definitions, as well as definitions as used here:

- Plant: system to be controlled (person)
- Control signal: signal used to control the plant (metronome)
- Controller / control system: system that determines and outputs the control signal
- Process variable: current status of the plant (actual speed)
- Set-point: desired value for the process variable (target speed)
- Perturbation: any unmeasured external effect that would cause the process variable to deviate from the set-point (wind, hills, etc.)

Design criteria and performance measures

The main design criteria for our speed control system were accuracy, responsiveness, robustness, stability and comfort.

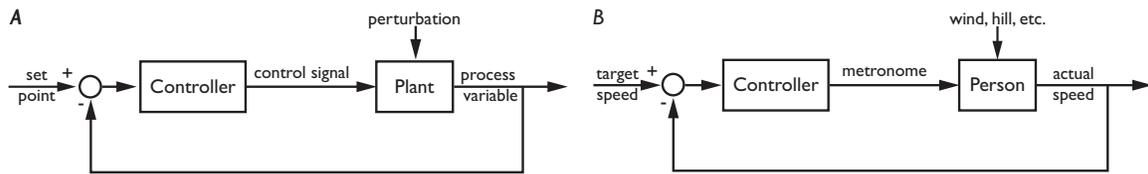


Figure B-1 Control system definitions

A) General definitions. B) Definitions as used in this study.

Accuracy

The accuracy of a system is defined as the level of correspondence between the set-point and the process variable⁷². Ideally, the difference between these two variables is as small as possible. We quantified the accuracy using the *steady-state error*, the difference between the target speed and the averaged actual speed once the speed following a change in target speed stabilized.

As a second measure of accuracy, we also determined the amount of variability of the actual speed around the target speed. We quantified this variability using the coefficient

of variation (root-mean-square-error between actual and target speed divided by the target speed).

Responsiveness

The responsiveness of a system determines how quickly it can respond to changes in the set-point, or to any external perturbations. The more responsive a system, the closer the process variable will be to the set-point during periods of non-steady state. To quantify the responsiveness we used the *settling time*, the time required for the actual speed to converge to within 5% of the final speed following a change in target speed.

Robustness

A control system is said to be robust if it performs well despite uncertainties, either in the plant or in external perturbations¹³⁶. Since we are aiming to control a complex biological system, such uncertainties are likely. It is highly unlikely that all the complexities underlying the relationship between prescribed step frequency and speed, including the variation between individuals and the effect of external perturbations, can be captured accurately. Indeed, in Chapter 3 we found that considerable variability existed in the relationship between prescribed step frequency and speed, both within and between individuals, which was not explained by our model. This variability leads to uncertainty in the person's behaviour when the speed control system is used. Hence, we are dealing with an uncertain system—in order for the speed control system to perform well for a range of individuals, and in a range of conditions, the system will need to be robust.

In general a trade-off exists between the robustness and responsiveness of a control system¹³⁷. In situations where a highly accurate model of the controlled process exists, the control system can be tuned to respond very quickly to set-point changes or perturbations, and thus deliver rapid and accurate control action. However, such *aggressive* control could have undesired effects if plant uncertainties are not accounted for. If such a highly accurate model of the controlled plant is not available, the general solution is to use more *conservative* control. Using more conservative control will decrease the responsiveness of the (nominal) system, but it will improve the overall robustness of the system thereby guarding against major system breakdowns. Given the considerable plant uncertainties we are dealing with here, we favoured robustness over dynamical performance when making design decisions.

Stability

Probably the single most important criterion when designing any control system is stability. Although many definitions of stability exist, here we will use the bounded-input-bounded-output (BIBO) stability definition. A system is BIBO stable if for any bounded input to the system the output is bounded as well. Although various measures of BIBO stability exist, here we will use the phase- and gain-margin to determine a system's stability (figure B-2). This method is especially useful as the phase- and gain-margin provide direct insight into the effects of plant variations on the stability of the controlled system. That is, it provides important insight in the robustness of the proposed controller. For example, the gain-margin specifies how much the loop gain of the system can change before the system reaches instability. Even though our plant is stable (the speed response following a change in prescribed step frequency converges to a finite value), it would be possible to create an unstable system by adding a controller. Thus, stability was certainly an important consideration when designing the speed control system.

Comfort

Comfort is not typically stated as a design criterion for control systems, but since we are attempting to control humans we believe this is very relevant here. Our main determinant of the comfort of the control system is the smoothness of the control signal. When controlling a typical electronic or mechanical system, a rapidly fluctuating control signal might be completely appropriate. For example, when the goal is to quickly rotate a DC motor from one position to the next, a good strategy would be to rapidly increase the control voltage to get the motor spinning, and then rapidly invert the voltage to stop it at the newly desired position. Here, such rapid fluctuations in the control signal would translate in rapid fluctuations in the frequency of the auditory stimulus, resulting in rapid changes in step frequency. Even if users would be able to keep up with such fluctuations these are undesirable. Thus, one of our design goals was to create a speed system that uses a smoothly changing metronome signal to control the user's speed.

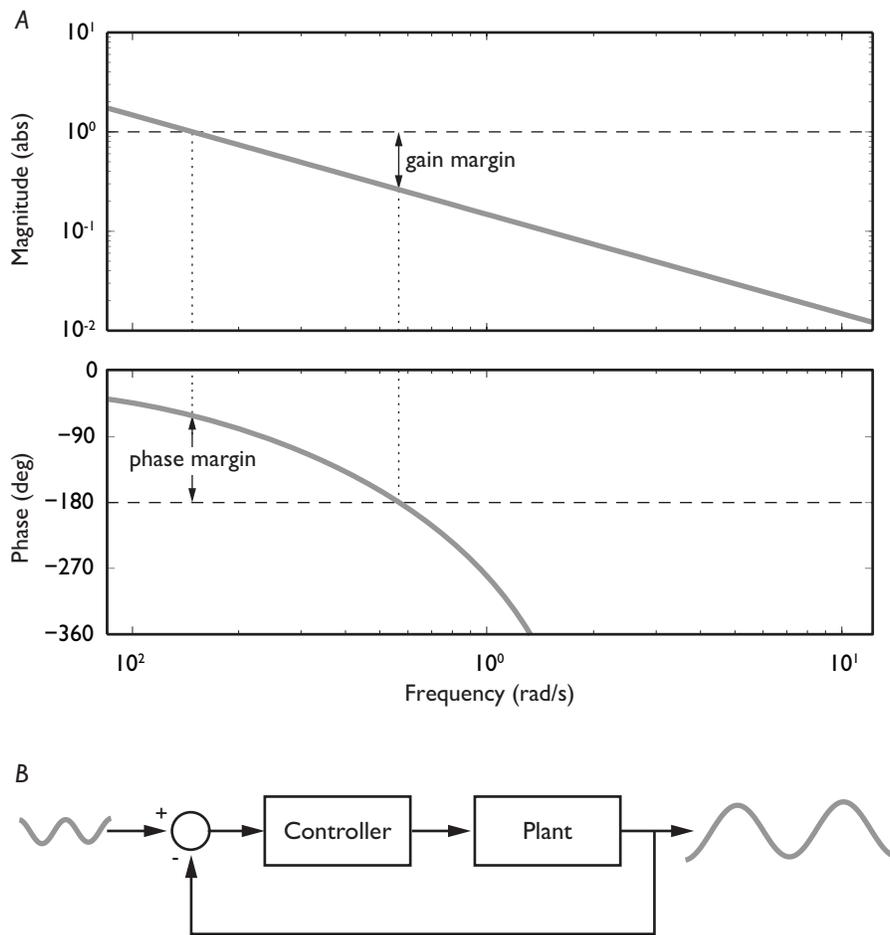


Figure B-2 Phase and gain margins

A) Bode plot showing phase and gain margins. A Bode plot is a graphical representation of the frequency response of a linear time-invariant (LTI) system. The response of an LTI system to an input sine-wave is again a sine-wave, with the same frequency but different magnitude and phase. The change in magnitude (gain) and phase depend on the frequency of the input sine-wave. In a Bode plot the gain (top) and phase shift (bottom) are given as a function of the input frequency. Since any signal can be decomposed into a series of sine-waves, the Bode plot provides a complete picture of the response of an LTI system to any input signal. A closed-loop system reaches instability if the gain exceeds unity when the phase delay reaches 180 degrees (see B). The gain- and phase margin determine the allowable change in gain and phase shift before the system reaches this instability. For example, the gain margin shows how much the gain could be increased before it is one, at the frequency where the phase delay is 180 degrees. The larger the gain- and phase margins, the more stable the system. B) Illustration explaining why a negative feedback system is unstable if the loop gain exceeds unity at the frequency where the phase delay reaches 180 degrees. A 180-degree phase delay basically results in inversion of the input signal. When the loop gain is larger than one, the signal at the output is an amplified and inverted version of the signal at the input. Through the negative feedback loop, the inverse of the output—which is an amplified version of the input—will be added to the input. The next time this composite signal runs through the system the exact same process will occur again, resulting in an ever-growing output signal. Even though the input is bounded (regular sine-wave), the output is unbounded as it is constantly growing. Thus, the system is BIBO unstable.

Controller structure

Our goal was to design a closed-loop speed control system to maximize performance for a large range of individuals and conditions. Although many different closed-loop control

strategies exist, by far the most popular is the *PID-controller* (proportional-integral-derivative controller, figure B-3). It has been estimated that over 95% of all industrial controllers used are of this particular type¹²⁰. Some of the reasons for the popularity of the PID-controller are the straightforward structure, robust performance in a wide variety of applications, and, owing to the fact that the controller has been used for over six decades, the existence of a variety of tuning rules^{137,138}. The benefits of different, often more complicated control strategies are mainly noticeable in systems with multiple inputs and/or outputs, or for systems containing significant nonlinearities¹³⁷. Since neither of these are a concern here, we will use the PID-controller structure.

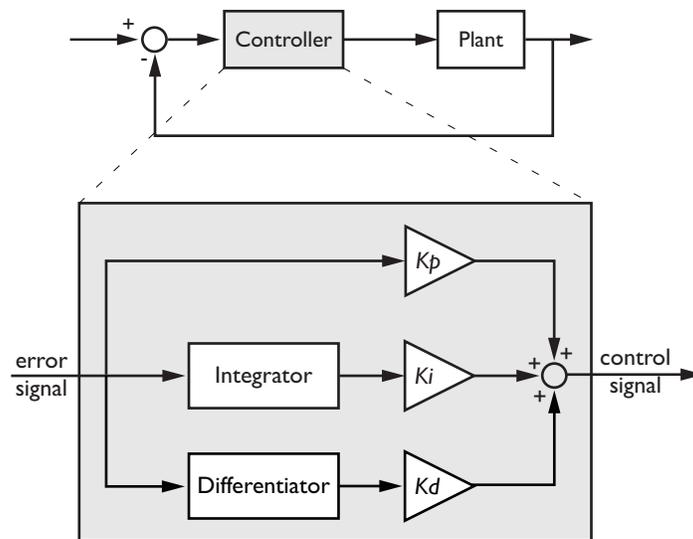


Figure B-3 Proportional-Integral-Derivative controller

The output of a PID controller is the sum of the proportional (p), integral (i) and derivative term (d). The contribution of each term is determined by the respective gain (K). In the speed control system developed here derivative control was not used, which is equivalent to setting K_d to zero.

Proportional control

When using proportional control, the control action applied to the plant depends proportionally on the error between the set-point and the process variable (figure B-3). As a consequence, the control action will be small when the error is small, and large when the error is large. Most car drivers use proportional control when controlling the speed of their car¹³⁹—when the car’s speed is slightly below the target speed, most drivers only lightly increase the pressure on the gas pedal. The larger the speed error, the more pressure the driver will apply. This graded control is an obvious improvement over the most simple form of control, where the driver could either completely depress

the pedal, or not at all (on/off control). The example of a driver controlling the speed of their car also demonstrates an important downside of proportional control used in isolation: anytime the car's speed equals the target speed the error is zero, resulting in the control signal and pressure on the gas pedal dropping to zero, even though a constant non-zero pressure is required to maintain speed (assuming non-zero drag and/or rolling resistance). As a consequence, when using only proportional control the car's speed will never actually equal the target speed (unless the target speed is zero). In fact, such 'steady-state error' will always be present when using just proportional control.

Integral control

Integral control solves the steady-state error present when using proportional control by integrating the error over time, and applying a control action proportional to this integrated error (figure B-3). As a consequence, the integral control action is not only based on the momentary error, but on the entire history of the error (thereby serving as something akin to the memory of the control system). To put this in our car driver analogy, whenever the speed of the car is equal to the target speed, the car driver knows that the car will remain at the target speed as long as they keep applying the same amount of pressure to the gas pedal (given that the speed is in steady state, and no external perturbations exist).

The main disadvantage of using integral control is that it can lead to oscillations in the process variable. To illustrate this issue, imagine that we are trying to control a very slow system. The integrated error will keep growing as long as an error exists between process variable and the set-point, resulting in an increasing output of the integral controller. By the time the process variable reaches the set-point, the output of the integral controller might have grown so much that it *overshot* the value required to maintain the process variable at the set-point. In this case, the process variable will keep rising past the set-point. As a consequence, the output of the integral controller will start decreasing. If this decrease happens too fast, the next time the process variable reaches the set-point it will keep decreasing past the set-point. Basically, whenever the proportionality constant of the integral controller (*integral gain*) is chosen too high, such oscillation of the process variable around the set-point will occur.

Derivative control

The final part of a standard PID-controller is derivative control, which applies a control action proportional to the derivative of the error (figure B-3). As a consequence, derivative control can respond to an error between the target and process variable before this error actually occurs. An example of derivative control in our car driving analogy is the increased pressure to the gas pedal whenever the car hits a hill. Instead of waiting for the speed to drop substantially, the driver can respond to the car slowing down. The main advantage of using derivative control action is that it can speed up the response of the system, and dampen oscillations⁷².

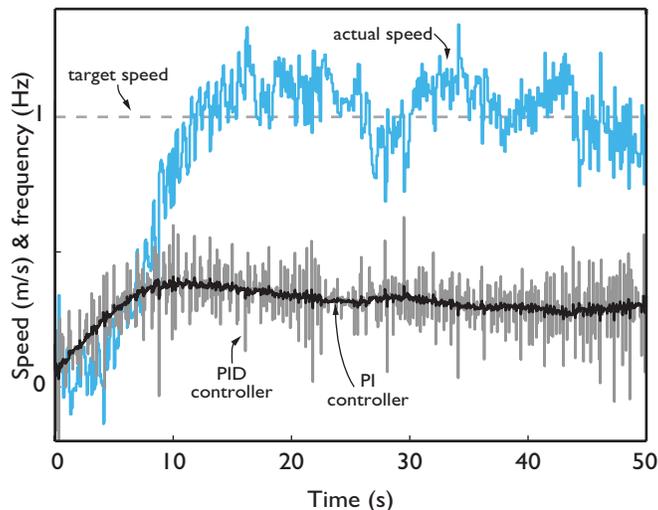


Figure B-4 Effect of using derivative control

Simulation results illustrating the effect of adding derivative control to the control system. As the disadvantage of derivative control only becomes apparent when noise is present in the process variable, we added a realistic amount of speed measurement noise to the speed (this noise was recorded during a representative run). The derivative gain was set to a very small value (0.001, about 50 times less than the proportional and integral gain used). Although the speed response is identical when using the PI- and PID-controller (hence only one actual speed signal, the other signal is completely hidden), the difference in the metronome signal outputted by the PI- and PID-controller is clear. The general solution to prevent such influence of noise on the control signal is to filter the speed measurement before using it for derivative control. However, this would further reduce the effect of the derivative control. This issue with derivative control is not unique to our application—the majority of PID-controllers used in process control are actually PI-controllers¹²⁰. Although derivative control is great in theory, it is often detrimental in practice.

The main disadvantage of using derivative control is that it is highly sensitive to noise—any rapid changes in the error will result in large fluctuations in the control signal (figure B-4). Since smoothness of the control signal was one of our main design criteria to ensure user comfort, we avoided using derivative control. The subset of PID-controllers using no derivative action (i.e. zero derivative gain) is commonly referred to as PI-

controllers (proportional-integral controllers). As we will show below, the use of a PI-controller is not expected to significantly decrease the performance of our control system compared to using a PID-controller. A combination of proportional and integral control action will prove sufficient to get the desired response when controlling a walking or running individual (at least in theory).

Control system tuning

To establish the desired performance and robustness characteristics the controller parameters need to be selected (*tuning*). As will become clear, the behaviour of the overall system varies dramatically with the choice of controller parameters, so careful *tuning* of the control system is highly important. Despite the presence of only two tuneable parameters in a PI-controller (the *proportional* and *integral gains*), tuning of these parameters is non-intuitive as the two parameters do not easily translate into the desired performance and robustness characteristics¹⁴⁰. Fortunately a number of tuning rules exist to simplify this process¹³⁸. Before we discuss the tuning rules used here and the actual tuning of the control system, we will first discuss the model of a walking/running individual used during this tuning, and the speed response that we would like to achieve.

Two-process model describing selection of preferred speed

Based on recent findings we have proposed that the selection of preferred gait patterns can be well described by the combined actions of two processes, acting over two distinct timescales⁶⁹⁻⁷¹. The first process acts very quickly, and is responsible for the majority of the gait adjustments following a change in, for example, walking speed. Although on average this fast process brings the current gait pattern to the preferred gait pattern, often the outcome of this fast process is not completely accurate. In this case the second, much slower, process is responsible for the actual convergence of the current gait pattern onto the preferred gait pattern. In Chapter 3 we showed that this two-process model accurately described the response in walking and running speed following changes in prescribed step frequency. Hence, this model will be the basis for the model used for tuning the speed controller parameters. However, even though our proposed two-process model is fairly straightforward already, we will simplify this model one step further before using it to determine the controller parameters.

Model reduction

Because *on average* the fast process brings the current speed to the preferred speed following changes in prescribed step frequency (figure B-5), when tuning the control system we ignored the presence of the slow process. Hence, the model of the plant dynamics used for tuning the control system was a simple first-order system, plus time delay (FOPDT system):

$$Y(s) = \frac{A}{\tau_s + 1} e^{-T_d s} \cdot X(s) \quad (\text{B-1})$$

Here, $X(s)$ is the input (metronome signal) and $Y(s)$ is the output (overground speed) in the frequency domain. Parameter A represents the amplitude of the speed change following a change in prescribed step frequency. This *frequency–speed gain* can be determined from the slope of the steady-state relationship between step frequency and speed. The second parameter, time constant τ , determines how quickly speed changes following a change in prescribed step frequency. Since we previously found that the fast process is responsible for the majority of the speed changes following a change in metronome frequency, we used the time constant of the fast process as the time constant for our reduced system. The final parameter, time delay T_d , simply describes how long it takes for a person to start reacting to a change in prescribed step frequency, and is equivalent to the time delay contained in the two-process model describing the control of locomotion.

The main reason for this model reduction is that it simplifies the tuning of the control system. As shown in figure B-5, the FOPDT system indeed accurately describes the average speed response to a change in prescribed frequency in both walking and running. Intuitively, this model reduction is possible since the fast process governs the majority of the speed response following changes in prescribed frequency. Any inaccuracies present in the fast process, and the rejection of these inaccuracies by the slow process, will be treated as perturbations and can conceptually be added to the other sources of uncertainty discussed previously. Simulation results demonstrating the effect of omitting the slow process are presented in figure B-6.

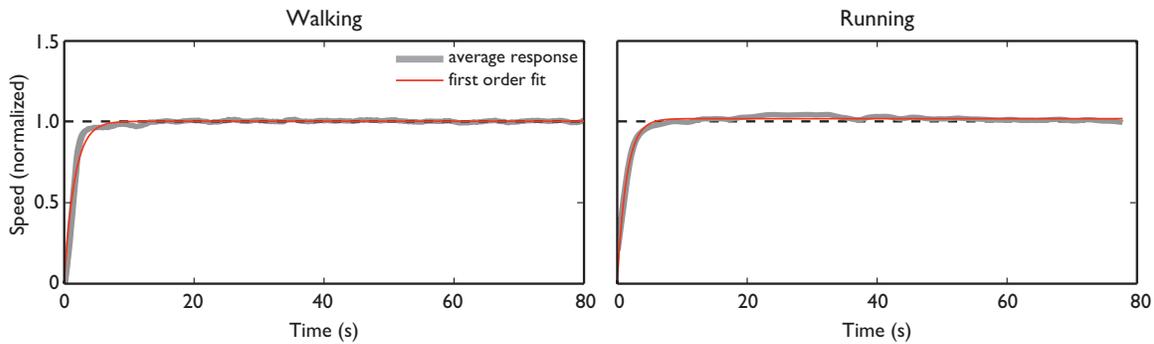


Figure B-5 Average speed response to a change in metronome frequency
 Average speed response following a change in prescribed step frequency during walking (left) and running (right), including best-fit first order model. The average speed response was determined by averaging the speed responses as found in Chapter 3 across all subjects and all trials. The R2 values for the first order fit were 0.97 for walking and 0.96 for running. It is clear that a first order model very accurately describes the average response.

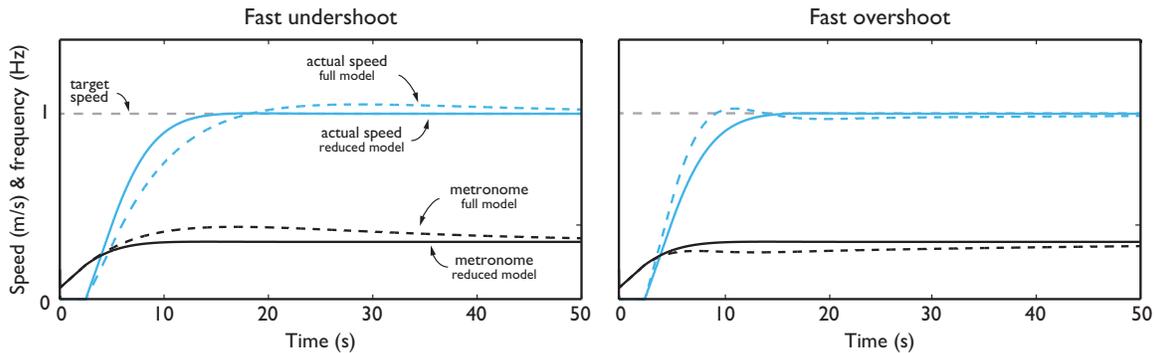


Figure B-6 Speed response of full versus reduced model
 Simulation results of speed responses following a step in target speed for the reduced model (only fast process) and full model (fast and slow process). The left and right hand figures illustrate the behaviour when the fast process undershoots or overshoots the final steady state value, respectively. For both simulations the fast process brought the speed to 30% of the final value. That is, the fast process (time constant 1.79s) had a normalized amplitude of 0.7 in the fast undershoot and 1.3 in the fast overshoot simulation. The remaining 30% was accounted for by the slow process (time constant 30s). The controller was tuned for the reduced model and was identical in all simulations. These results suggest that a controller that is tuned for a system assuming only a fast process delivers acceptable performance when applied to a system containing both a fast and a slow process, even when the contribution of the slow process is substantial.

Desired response

To make sure that our speed control system will be comfortable to use, our preferred speed response following changes in target speed was a gradual convergence towards this target speed, with minimal overshoot and oscillations. That is, the preferred response would resemble the response of a simple first-order system. When the change in target speed is a step function, the desired response v can be described by the following equation:

$$v = A \left(1 - e^{-\frac{v-T_d}{\tau_r}} \right) + v_0 \quad (\text{B-2})$$

where v_0 is the speed prior to the change in target speed, A is the slope of the frequency–speed relationship, T_d is the physiological delay present in the speed response, and τ_r is the time constant of the desired response. Ideally, the desired response would not include a time delay, but the existing delay is unavoidable as this delay includes factors such as the time it takes for a person to perceive that the control signal (metronome) changed and to respond to this change. No matter how good the control system would be, these physiological delays would always be present in the response.

Simple internal model control

To select the proportional and integral gain for our control system we used the *simple internal model control* tuning rules as described by Skogestad¹¹¹. The basic idea underlying these tuning rules is *direct synthesis* – given the model of the controlled plant and the desired closed-loop response, the corresponding controller can be solved for analytically. Skogestad showed that when starting with an FOPDT system, and specifying the desired output as a first-order process plus time delay (equation B-2), the optimal controller structure is a PI-controller. So, even though we decided to avoid derivative control action and use a PI-controller based on heuristic reasoning, it turns out that this is actually the optimal controller structure given our reduced model and desired response. Besides leading to the optimal controller structure, the direct synthesis approach also gives expressions for the optimal controller gains:

$$K_P = \frac{1}{A} \cdot \frac{\tau}{T_d + \tau_r} \quad (\text{B-3})$$

$$K_I = \frac{K_P}{\tau} \quad (\text{B-4})$$

where K_P and K_I are the proportional and integral gain, respectively. A , τ and T_d are the parameters from the FOPDT system described above, and describe the plant under control. Once these plant parameters are known, the proper proportional and integral

gain can be calculated by specifying τ_r , the time constant of the desired response. Hence, instead of tuning the proportional and integral gain separately, these can be determined directly from the desired response. The trade-off between speed of response on one side and stability and robustness on the other side depends on the choice of the τ_r , with a larger time constant leading to improved stability and robustness.

Tuning for the ‘worst-case’ individual

To reiterate, the goal of our study was to develop a speed control system that works well for a large range of individuals. As shown in Chapter 3, significant variations existed between individuals in their speed response following changes in prescribed frequency. As the parameters A , τ , and T_d used to model these responses (equation B-1) are used in equations B-3 and B-4 to determine the controller settings, an important decision was what values to use for these parameters. To illustrate the importance of this decision, the simulated speed response of two individuals is shown in figure B-7—for both simulations the same settings for the speed control system were used, only the models of the persons were different (both within realistic range based on our findings in Chapter 3). As the speed control system used for these simulations lacks robustness against changes between individuals it would not be acceptable.

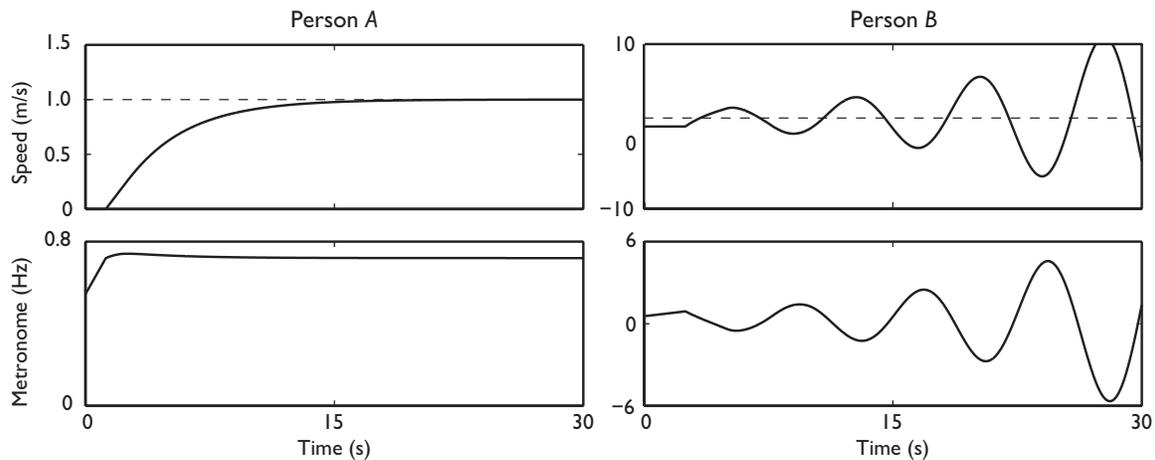


Figure B-7 Effect of between person variability on controlled response

Simulation of prescribed step frequency (bottom) and speed response (top) for two individuals following a step in target speed (dashed line). For both simulations the exact same settings for the speed control system were used, only the person model was different. Person A was simulated using the shallowest frequency–speed slope, longest time constant and shortest delay as found in Chapter 3. Person B was simulated using the steepest frequency–speed slope, shortest time constant, and longest delay as found in Chapter 3. The control system was tuned using the model of person A. Although the resulting controller works well for person A, it causes instability for person B. Thus, this controller is not robust against changes between individuals.

We decided to determine the controller settings assuming the ‘worst’ (that is, least stable) combination of the parameters A , τ , and Td . If the system is stable for this ‘worst-case’ individual, the system is guaranteed to be stable for individuals with any other combination of these three parameters (at least within the range found in Chapter 3). The effects of variations in A , τ , and Td on the stability of the controlled system are shown in figure B-8. The effects of changes in the frequency–speed gain (A) and time delay (Td) are clear—the stability will decrease whenever these parameters increase. The opposite is true also—whenever these parameters decrease, the overall stability will increase. As a consequence, when tuning the speed control system for the maximum values of A and Td , any changes in these parameters would increase the system’s stability. Hence, the maximum values for A and Td will be used to determine the default controller settings. The effect of changes in the time-constant is less obvious—with decreasing time constant the gain margin decreases (decreased stability) but the phase margin increases (increased stability). Hence, it is more difficult to determine the changes in stability caused by changes in the time constant. To get a better insight in the results of tuning the system using a slow or fast time constant we performed computer simulations (figure B-9). Based on these simulation results we decided to use the fastest (minimum) value for τ to determine the default controller settings, because this decreases the chance of any irregularities in the control signal.

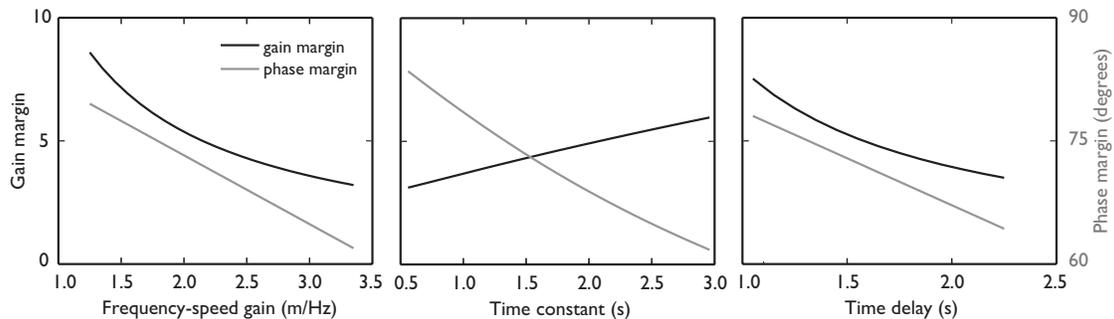


Figure B-8 Effect of parameter variations on gain- and phase margins

The ranges used for the frequency–speed gain, time constant, and time delay are the ranges found in the running experiment in Chapter 3. The system becomes less stable when either the frequency–speed gain or time delay increase, as illustrated by the decrease in both the gain- and phase margin. The effect of changes in the time constant on the systems stability is less clear, as the gain- and phase margin move in opposite direction. Here, we are mainly interested in the trend of the gain- and phase margin with changes in the parameters, as opposed to the actual values.

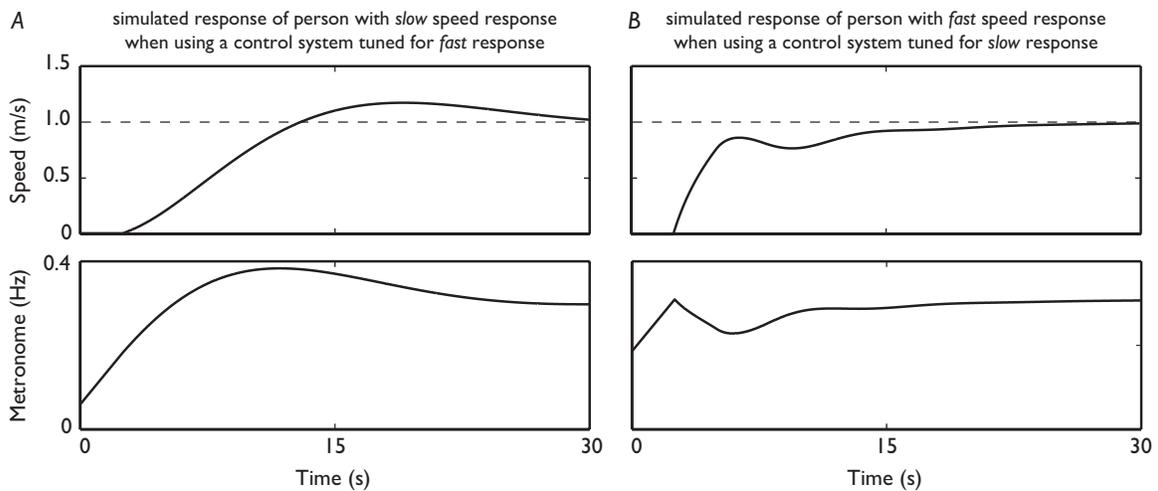


Figure B-9 Effect of tuning for different values of the time constant on the controlled response

Simulation of the prescribed step frequency (bottom) and speed response (top) following a step change in target speed (dashed line), for control systems tuned using different settings for the person's time constant. A) The settings for the control system used in this simulation were determined using the fastest value of the time constant as found in Chapter 3. The person used in the simulation was the same as used for determining the controller settings, except that the time constant was slower. The behaviour of a speed control system tuned assuming a fast time constant, and applied to an individual with a slow time constant, is an overshoot in the prescribed step frequency and speed response. B) The settings for the control system used in this simulation were determined using the slowest value of the time constant as found in Chapter 3. The person used in the simulation was the same as used for determining the controller settings, except that the time constant was faster. The behaviour of a speed control system tuned assuming a slow time constant, and applied to an individual with a faster time constant, is an irregularity in the metronome signal. As we considered smoothness of the metronome signal an important design criterion to ensure user comfort, we decided to use the fastest time constant to determine the default controller settings. If the actual user would have a slower time constant than used to determine the controller settings, their response would tend towards the response shown in figure A. Thus, using a fast time constant to determine the controller settings ensures a smooth control signal for a large range of individuals.

In summary, we used the maximum frequency–speed gain and time delay, and the minimum time constant, to determine the default controller settings. The effects of parameter changes when using these default settings are shown in figure B-10. Although the controlled behaviour is stable for all variations in parameters shown (and, although not shown, for all combinations of parameter changes), when using the default settings the predicted speed response is very slow for some individuals. We will improve this response by using an *adaptive controller*.

Adaptive control

Although the default controller settings are expected to result in a robust control system, for some individuals it would result in quite slow convergence to the target speed (figure B-10). One possibility to improve the performance of the controller for these individuals

would be to make the controller *adaptive*. The fundamental idea underlying adaptive control is to modify the control system based on knowledge of the plant parameters gathered in real-time¹²⁰. In our speed control system, the one piece of information about the current user that would be relatively easy to determine in real-time would be the slope of the steady-state relationship between prescribed step frequency and speed (using, for example, a recursive regression). As shown in figure B-10 this gain has a strong effect on the speed of the response, so an improved knowledge of this gain could perhaps be leveraged to accelerate the dynamical response. Indeed, it can be shown mathematically that adapting the controller settings based on an improved estimate of the frequency–speed gain essentially cancels the effect of this gain. That is, if the controller settings were adapted based on the frequency-speed gain for each participant, the dynamic response should in theory be identical for all participants despite the variability in their frequency-speed gain. Here, instead of adapting the controller settings on-line, we used the predetermined frequency–speed slope for each subject to determine the individual controller settings prior to the experiment. This allowed us to test the performance of the adapted controller without the added complication of implementing a control system that was adapting in real-time.

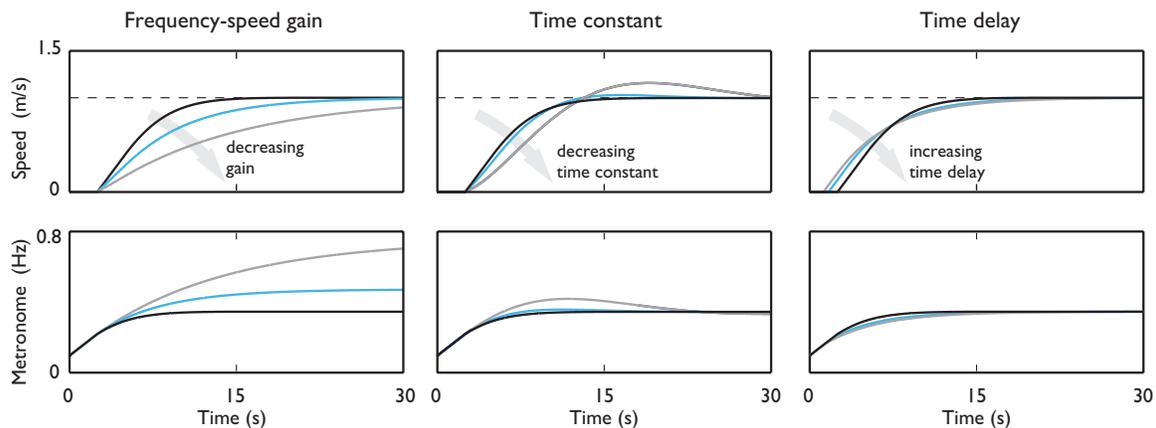


Figure B-10 Effect of between individual variability on the controlled response
 Effect of parameter variations on speed response (top) and metronome signal (bottom) following a unit step (dashed line) in the target speed when using the default controller setting. The ranges used for the frequency–speed gain, time constant, and time delay are the ranges found in the running experiment in Chapter 3. The grey, blue and black lines are produced using respectively the minimum, mean and maximum value for the parameters. Especially the range of the frequency-speed gain (left hand plot) has a large effect on the speed response and the metronome signal required. To drive an individual with a lower frequency-speed gain to the target speed requires more time, and a larger change in metronome frequency.

Final controller settings

We tested both the default and individual controller settings in all participants. To determine the final settings, we had to specify the time constant of the desired response (equations B-3 & B-4). The time constant for the desired running response was set equal to the slowest time constant found in Chapter 3 (3.8 seconds). This was slightly longer than recommended by Skogestad¹¹¹, who recommended that the response time constant be set equal to the time delay. Simulation results showed that using the maximum time constant instead of the maximum time delay ensured smooth control signals for all combinations of frequency–speed gains, time constants and time delays found in Chapter 3. Since smoothness of the control signal was one of our design criteria, we preferred this slightly longer time constant. The resulting default proportional and integral gain used for the control of running speed was 0.06 and 0.05, respectively. Based on the results of a pilot study, for walking we decided to use a slightly slower desired time constant (7 seconds). This slower time constant resulted in more gradual changes in the prescribed step frequency, which was preferred by the participants in our pilot experiment. The resulting default proportional and integral gain used for the control of walking speed was 0.13 and 0.10, respectively. The individual controller settings for each participant are shown in table B-1. Note that for easier visualization of the data we discuss the dynamic response results in terms of response time instead of time constant. The response time is the time required for the subject to reach 95% of the new target speed. The response time is equal to three times the time constant. Thus, the desired response time was 11.4 seconds in running, and 21 seconds in walking.

	Frequency-speed slope	Proportional gain	Integral gain
Walking			
Subject 1	1.03	0.14	0.11
Subject 2	0.91	0.16	0.13
Subject 3	0.92	0.16	0.13
Subject 4	0.80	0.19	0.15
Subject 5	0.97	0.15	0.12
Running			
Subject 1	3.25	0.06	0.05
Subject 2	2.97	0.07	0.05
Subject 3	3.08	0.06	0.05
Subject 4	2.70	0.07	0.05
Subject 5	1.58	0.10	0.12
Subject 6	0.90	0.18	0.22

Table B-1 Individual controller settings for speed control system

Individual controller settings during the walking and running experiment. These controller settings were calculated by adjusting the default controller settings using the individual slope of the frequency-speed relationship for each subject.

Appendix C.

Closed-loop speed control questionnaire

Run 1:

1. Please rate your level of perceived exertion:
2. How did it feel?
3. How much change did you perceive in the metronome frequency?
 - 1: The metronome frequency was clearly changing constantly
 - 2: The metronome frequency clearly changed periodically – between these obvious changes the metronome frequency was constantly changing by small amounts
 - 3: The metronome frequency clearly changed periodically – between these obvious changes the metronome frequency was constant
 - 4: The metronome frequency was constant
 - 5: Other:
4. How much change did you perceive in your running speed?
 - 1: My speed was clearly changing constantly
 - 2: My speed clearly changed periodically, between these obvious changes my speed was constantly changing by small amounts
 - 3: My speed clearly changed periodically, between these obvious changes my speed was constant
 - 4: My speed was constant
 - 5: Other:

General

1. How would you rate the use of sound to control your running speed in terms of comfort?
 - 1: Very uncomfortable
 - 2: Uncomfortable
 - 3: Comfortable
 - 4: Very comfortable
 - 5: Other:

2. How likely would you be to use the speed control system during your training runs, assuming that the system is comparable in size to existing training devices?
 - 1: Very unlikely
 - 2: Unlikely
 - 3: Likely
 - 4: Very likely
 - 5: Other:

3. How likely would you be to use the speed control system during your races, assuming that this is allowed and the system is comparable in size to existing training devices?
 - 1: Very unlikely
 - 2: Unlikely
 - 3: Likely
 - 4: Very likely
 - 5: Other:

4. Did you notice a difference between the two trials? If so, can you describe this difference? Which of the trials, if any, did you prefer?

Appendix D.

Methods and Systems for Control of Human Locomotion

(54) **METHODS AND SYSTEMS FOR CONTROL OF HUMAN LOCOMOTION**

(75) Inventors: **Mark Snaterse**, Port Moody (CA); **Sung Jae Chang**, Toronto (CA); **James Maxwell Donelan**, North Vancouver (CA)

(73) Assignee: **SIMON FRASER UNIVERSITY**, Burnaby, BC (CA)

(21) Appl. No.: **13/808,886**

(22) PCT Filed: **Jul. 7, 2011**

(86) PCT No.: **PCT/CA11/50417**

§ 371 (c)(1),

(2), (4) Date: **Jan. 7, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/362,170, filed on Jul. 7, 2010.

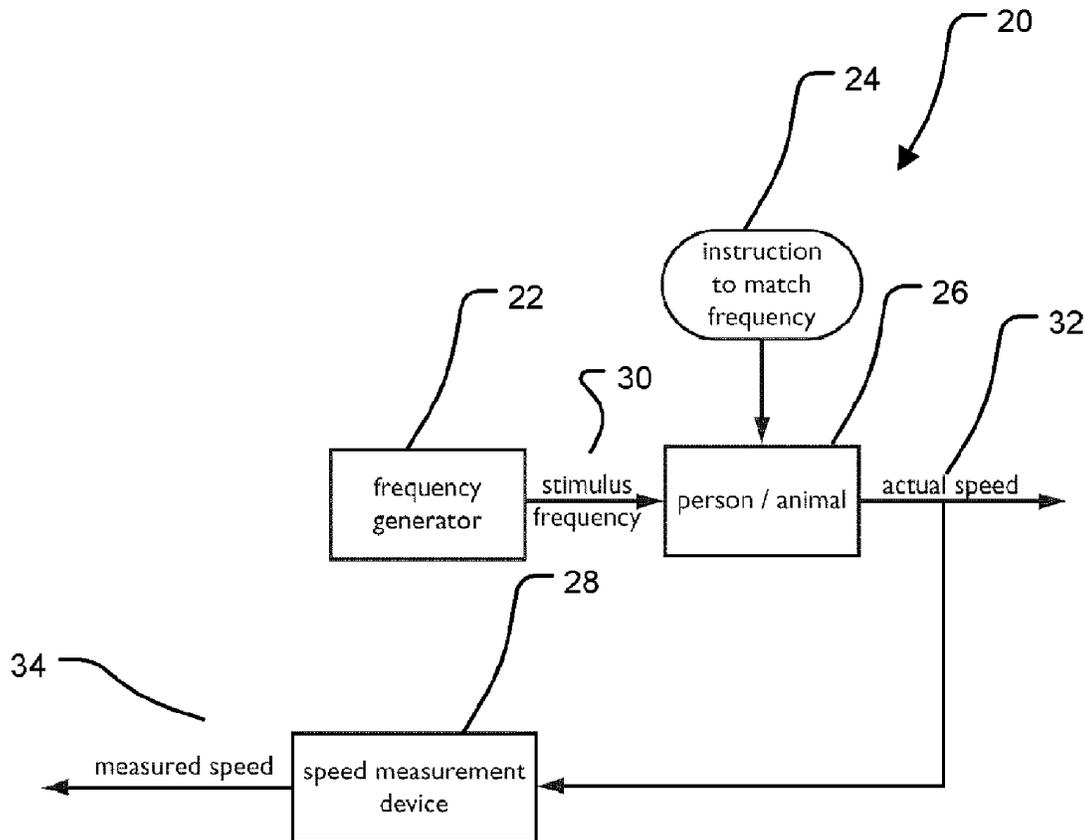
Publication Classification

(51) **Int. Cl.**
G06F 17/40 (2006.01)

(52) **U.S. Cl.**
CPC **G06F 17/40** (2013.01)
USPC **700/91**

(57) ABSTRACT

A method is provided for the automatic control of locomotion speed in a human or other animal subject. The method comprises: estimating the subject's actual locomotion speed using one or more sensors to thereby obtain a measured speed; determining an error comprising a difference between a desired speed and the measured speed; and outputting, to the subject, a stimulus frequency signal wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual speed controllably tracks the desired speed.



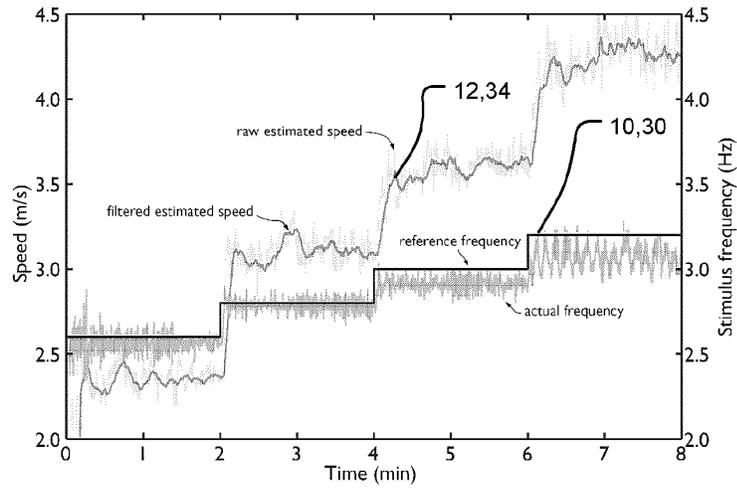


FIGURE 1A

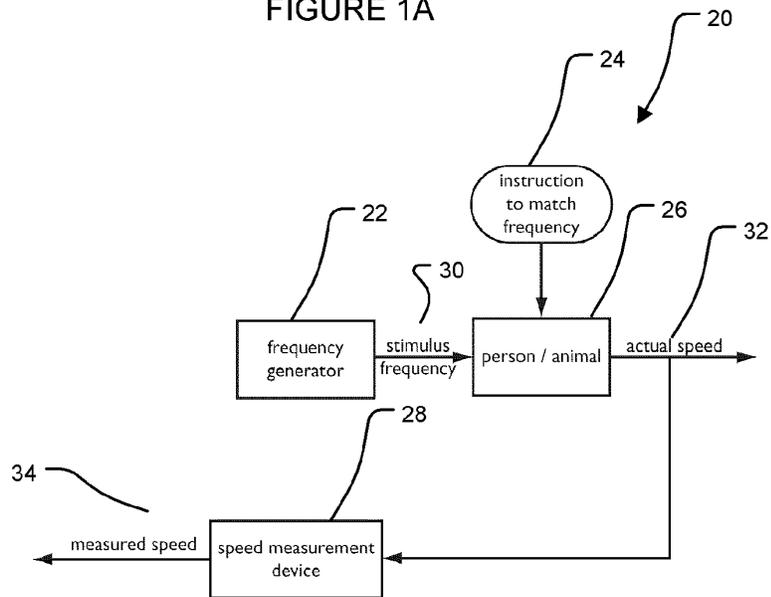


FIGURE 1B

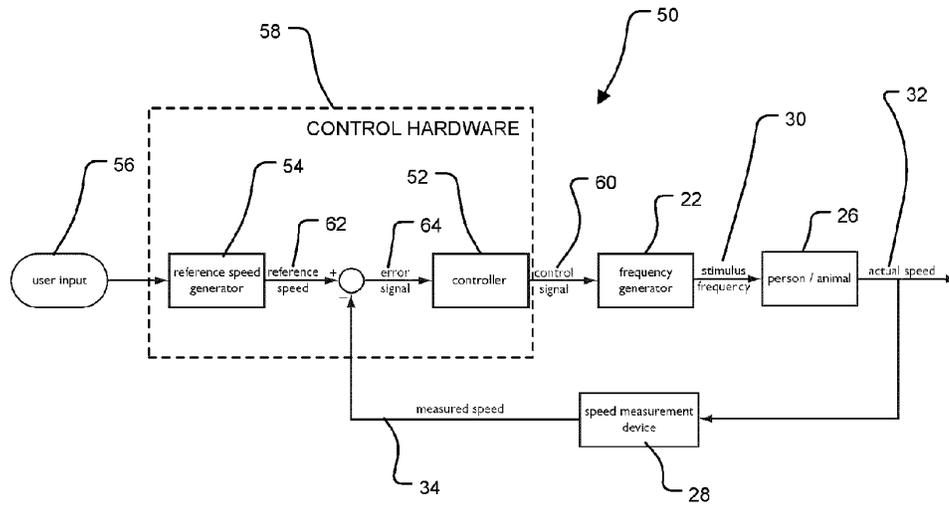


FIGURE 2

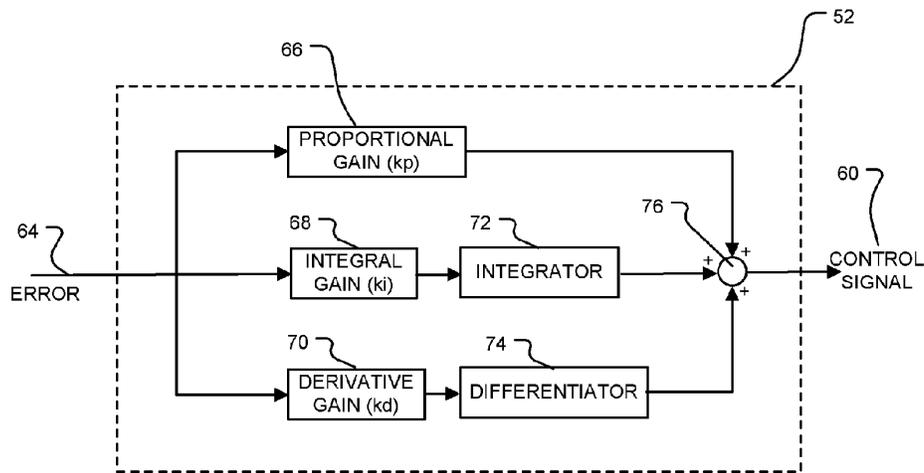


FIGURE 3

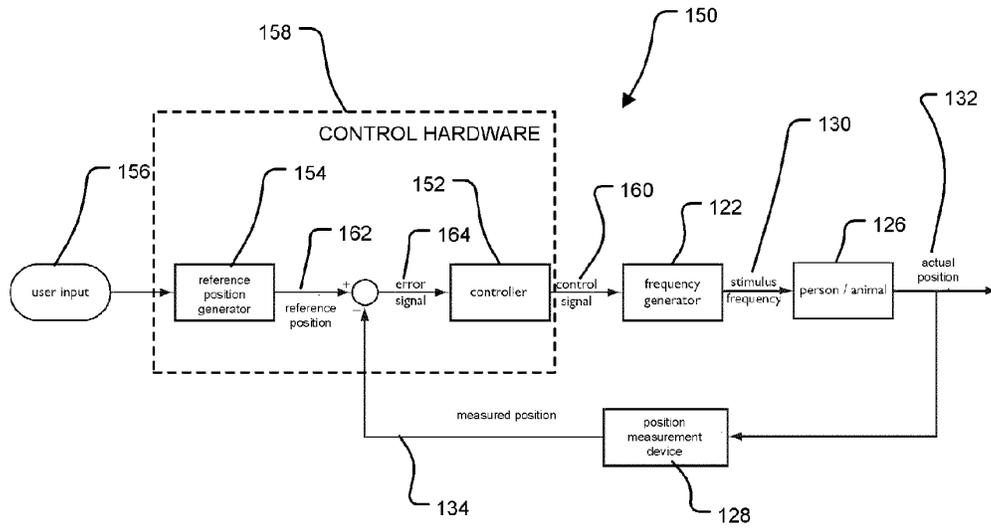


FIGURE 4

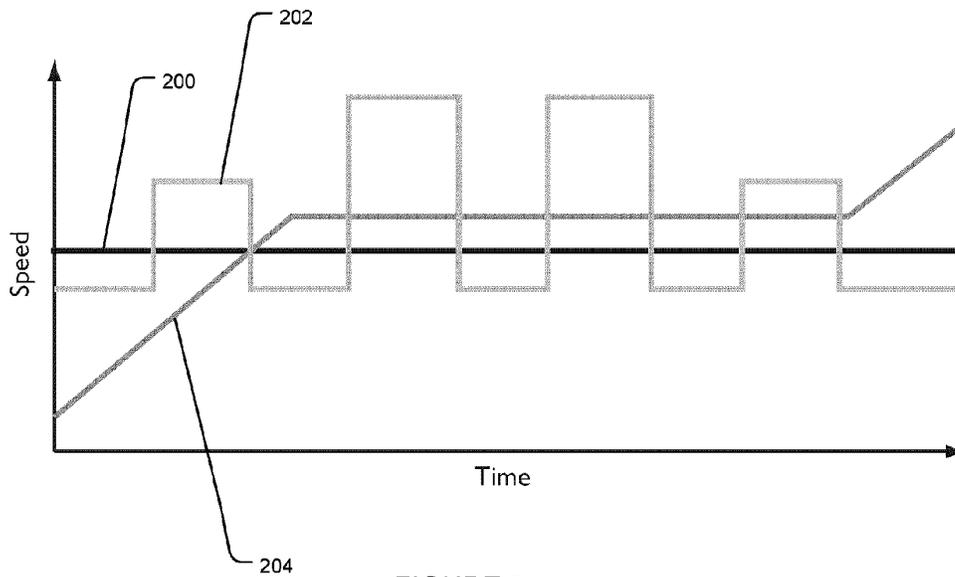


FIGURE 5

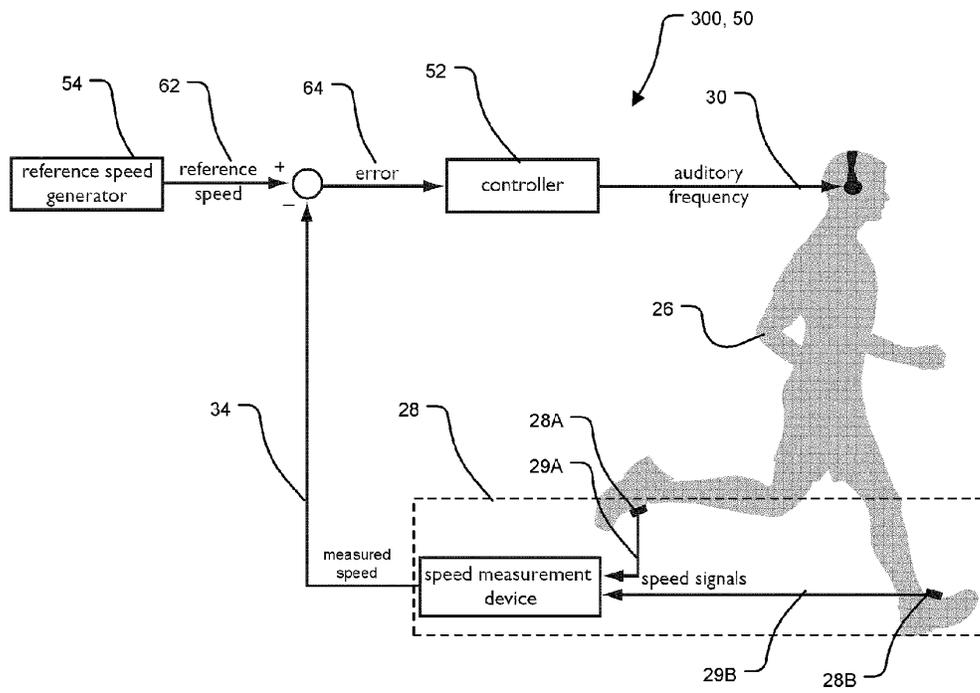


FIGURE 6

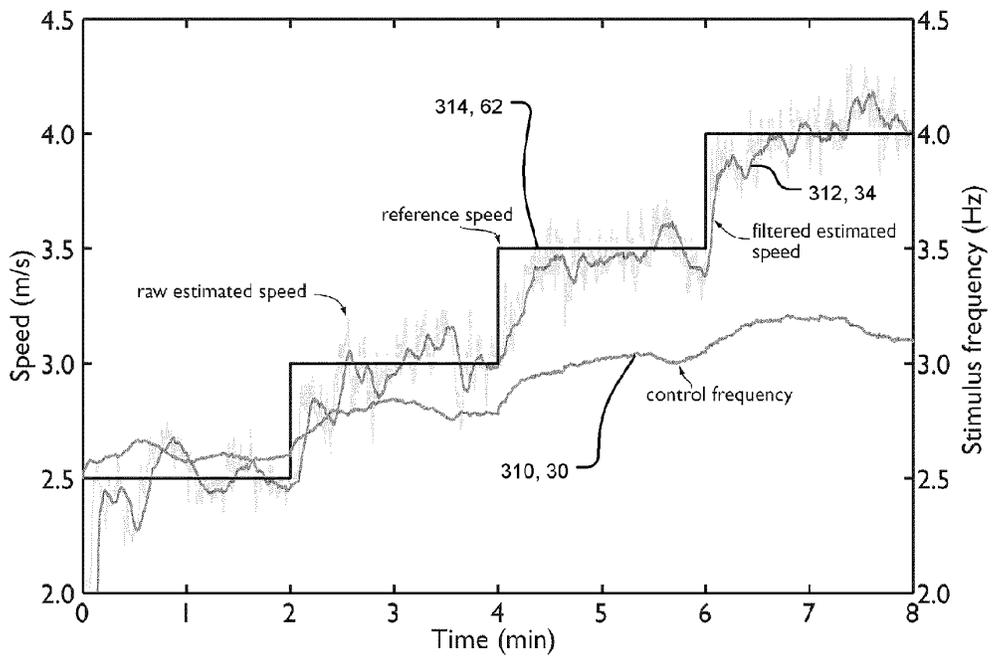


FIGURE 7

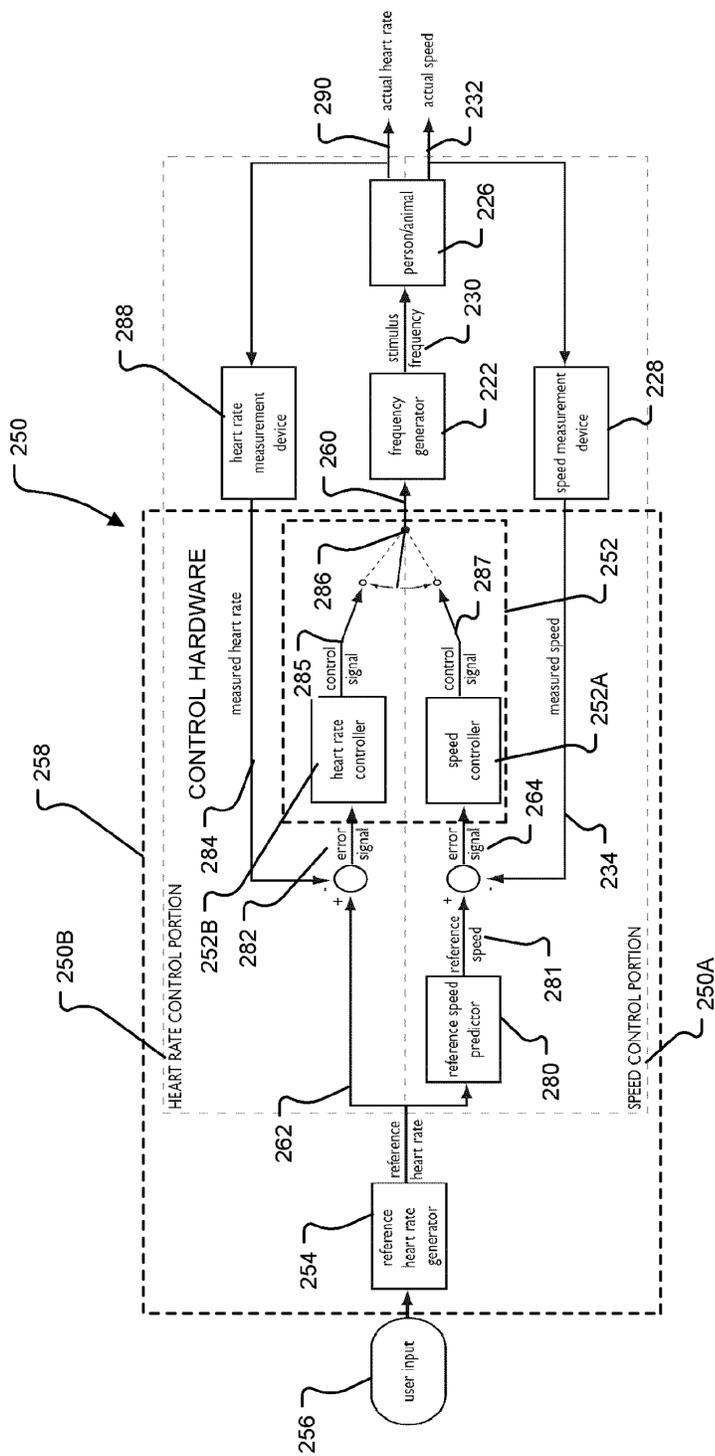


FIGURE 8

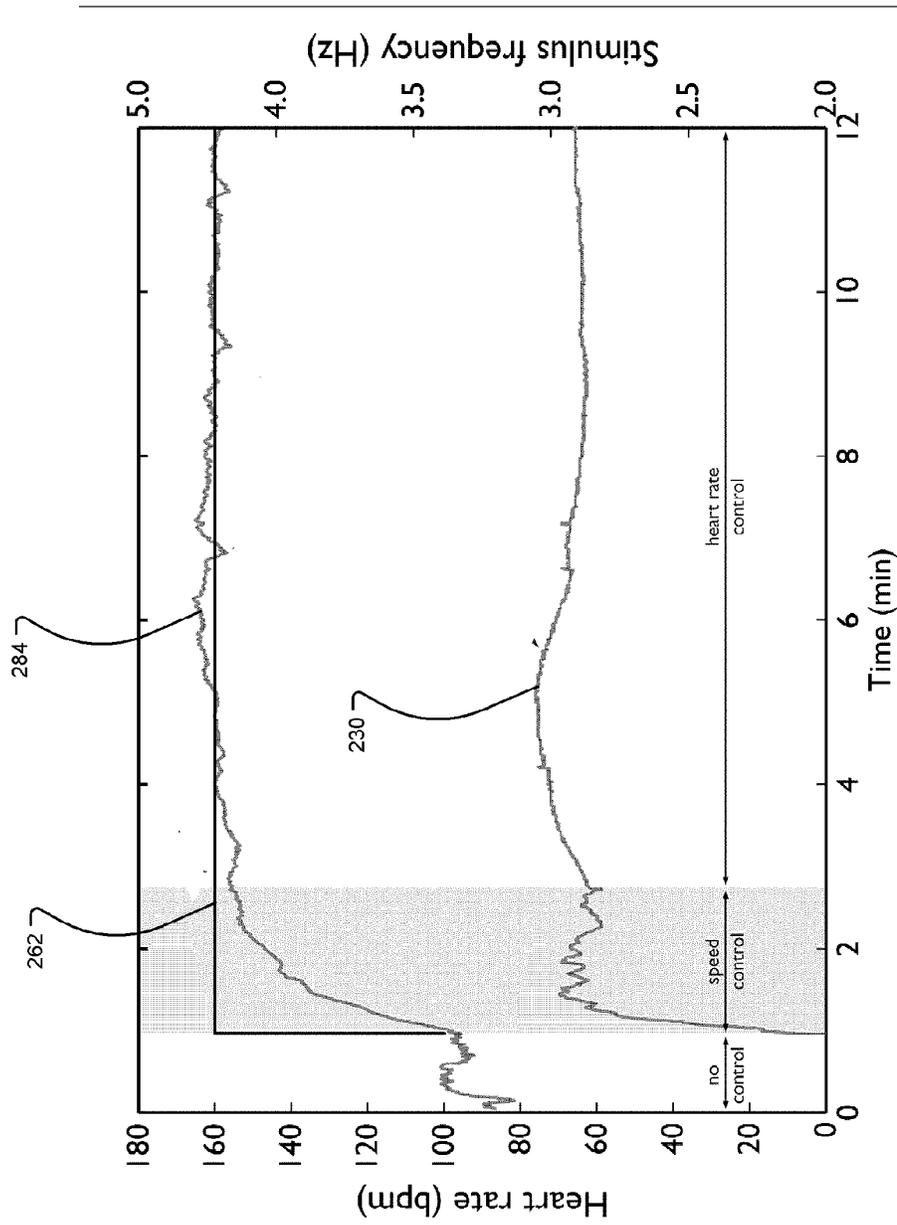


FIGURE 9

METHODS AND SYSTEMS FOR CONTROL OF HUMAN LOCOMOTION

RELATED APPLICATIONS

[0001] This application claims the benefit of the priority of U.S. application No. 61/362170 filed 7 Jul. 2010 which is hereby incorporated herein by reference. For the purposes of the United States, this application claims the benefit of U.S. application No. 61/362170 filed 7 Jul. 2010 under 35 USC §199(e).

TECHNICAL FIELD

[0002] This invention relates to the automatic control of human locomotion (e.g. running and/or walking). Some embodiments provide methods and systems for automatic control of human locomotive speed, position and/or intensity.

BACKGROUND

[0003] There is a general desire to describe and/or control various means of human locomotion. Such description and/or control can assist with navigation, predicting arrival times and the like. For example, the description of the speed of an automobile (e.g. provided by a speedometer) may be used to predict how far the automobile can travel in a particular length of time and/or when the automobile will arrive at a particular destination. Speed control of the automobile (e.g. provided by a cruise control system) can be used to achieve target arrival times, target speeds and the like.

[0004] There is a similar desire to describe and/or control human locomotion (e.g. locomotion, such as running, walking and/or the like).

[0005] Like the case of the exemplary automobile discussed above, such control can assist with achieving target navigation parameters, such as arrival times and the like. By way of non-limiting example, description and control of human locomotion can also have application to training (e.g. for athletes, recreational runners, soldiers and the like). Many runners, ranging from world class athletes to recreational runners, set objectives (goals) to cover a given distance in a certain amount of time. To achieve such objectives, such runners have to run the distance at a particular speed or with a particular speed profile.

[0006] Various systems and techniques are known in the prior art to estimate running/walking speed and/or position. Such prior art systems include:

[0007] The “Nike+”™ sportsband developed by Nike, Inc and the “Rock and Run” system developed by Apple Inc. in conjunction with Nike, Inc. use an in-shoe sensor and a handheld or band-mounted user interface to estimate time, distance and speed and to provide such information to the shoe wearer—(see http://nikerunning.nike.com/nikeos/p/nikeplus/en_EMEA/sportband and <http://www.apple.com/ipod/nike/run.html>).

[0008] The “Forerunner”™ series of wrist-worn devices sold by Garmin Ltd. which use global positioning system (GPS) technology to estimate position, speed and time and to provide such information to the user—(See https://buy.garmin.com/shop/shop.do?cID=141&fKeys=FILTER_SERIES_FORE_RUNNER).

[0009] The “Polar S3 Stride Sensor W.I.N.D.”™ sensor sold by Polar Electro Oy which mounts to the user’s shoe, measures the acceleration of a user’s foot and uses

this acceleration information to estimate ground speed and/or distance—(http://www.polarusa.com/us-en/products/accessories/s3_Stride_Sensor_WIND).

[0010] The “Speedmax”™ technology developed by Dynastream Innovations Inc. which uses inertial sensors to detect running/walking speed and distance.

[0011] Other than for providing the user with information about their speed, however, these systems and techniques do not appear to permit automatic control of human running/walking speed and/or position. Using such systems, a user would have to repetitively monitor the user interface (or repetitively receive output from an output device (e.g. head-phones)) and then the user would have to determine on their own whether they were meeting their speed objective. Based on their own consideration of whether they were meeting their speed objective, the user would then have to adjust their speed on their own and then recheck the user interface at a later time to determine if their new speed meets the speed objective. For most humans, this speed adjustment is difficult to perform accurately. No information is provided to the user between the time that the user first checks the user interface and the time that the user subsequently rechecks the user interface at the later time. These systems are analogous to the speedometer of an automobile, wherein speed information is provided to the driver, but the driver adjusts the speed on their own (i.e. without automatic cruise control). Such systems do not provide automatic speed control of locomotion in a manner that is analogous to cruise control in an automobile.

[0012] There is a desire for systems which help a subject to automatically control a speed and/or position of their human locomotion (e.g. locomotion such as running and/or walking).

[0013] In addition to or in the alternative to controlling locomotive speed and/or position, there is a general desire to control locomotion intensity. Locomotion intensity is usually estimated based on one or more measurable or estimatable or measurable intensity indicators. Such intensity indicators include, by way of non-limiting example, hear rate, metabolic rate, oxygen consumption, perceived exertion, mechanical power and/or the like.

[0014] Various systems and techniques are known for estimating hear rate. Such systems include:

[0015] Strapped heart rate monitors (for example by Polar Electro Oy—see http://www.polarusa.com/us-en/products/get_active); and

[0016] Strapless heart rate monitors (for example by Physi-Cal Enterprises Inc.—see http://mioglobal.com/main_products).

Again, as is the case with speed measurement, these heart rate monitors merely provide the user with information about their heart rate and do not appear to permit automatic control of the intensity of human locomotion. Accordingly, these systems suffer from analogous drawbacks to those of the speed and distance measurement systems described above.

[0017] There has been some attempt in the art at control of a user’s heart rate. Examples may include the BODIBEAT™ music player marketed by Yamaha—see <http://www.yamaha.com/bodibeat/consumer.asp>; and the TRIPLEBEAT™ application marketed by the individual Dr. Nuria Oliver—see <http://www.nuriaoliver.com/TripleBeat/TripleBeat.htm>.

SUMMARY

[0018] The following embodiments and aspects thereof are described and illustrated in conjunction with systems, tools

and methods which are meant to be exemplary and illustrative, not limiting in scope. In various embodiments, one or more of the above-described problems have been reduced or eliminated, while other embodiments are directed to other improvements.

[0019] One aspect of the invention provides a method for the automatic control of locomotion speed in a human or other animal subject. The method comprises: estimating the subject's actual locomotion speed using one or more sensors to thereby obtain a measured speed; determining an error comprising a difference between a desired speed and the measured speed; and outputting, to the subject, a stimulus frequency signal wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual speed controllably tracks the desired speed.

[0020] Another aspect of the invention provides a method for the automatic control of locomotion position of a human or other animal subject. The method comprises: estimating the subject's actual locomotion position using one or more sensors to thereby obtain a measured position; determining an error comprising a difference between a desired position and the measured position; and outputting, to the subject, a stimulus frequency signal wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual position controllably tracks the desired position.

[0021] Another aspect of the invention provides a method for the automatic control of locomotion intensity in a human or other animal subject. The method comprises: estimating the subject's actual locomotion intensity using one or more sensors to thereby obtain a measured intensity; and determining an intensity error comprising a difference between a desired intensity and the measured intensity. If an absolute value of the intensity error is outside of a threshold region around the desired intensity, then the method involves: estimating the subject's actual locomotion speed using one or more sensors to thereby obtain a measured speed; converting the desired intensity to a desired speed; determining a speed error comprising a difference between the desired speed and the measured speed; and outputting, to the subject, a speed-based stimulus frequency signal wherein the speed-based stimulus frequency signal is based on the speed error in such a manner that when the subject ambulates in a manner that matches a frequency of the speed-based stimulus frequency signal, the subject's actual intensity controllably tracks the desired intensity. If the absolute value of the intensity error is within the threshold region around the desired intensity, then the method involves outputting, to the subject, an intensity-based stimulus frequency signal wherein the intensity-based stimulus frequency signal is based on the intensity error in such a manner that when the subject ambulates in a manner that matches a frequency of the intensity-based stimulus frequency signal, the subject's actual intensity controllably tracks the desired intensity.

[0022] Another aspect of the invention provides a system for automatically controlling a locomotion speed of a human or other animal subject. The system comprises: one or more sensors for sensing one or more corresponding parameters of the locomotion movement of the subject and for generating therefrom a measured speed which represents an estimate of the subject's actual locomotion speed; a controller configured

to: determine an error comprising a difference between a desired speed and the measured speed and output, to the subject, a stimulus frequency signal; wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual speed controllably tracks the desired speed.

[0023] Another aspect of the invention provides a system for automatically controlling a locomotion position of a human or other animal subject. The system comprises: one or more sensors for sensing one or more corresponding parameters of the locomotion movement of the subject and for generating therefrom a measured position which represents an estimate of the subject's locomotion position; a controller configured to: determine an error comprising a difference between a desired position and the measured position and output, to the subject, a stimulus frequency signal; wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual position controllably tracks the desired position.

[0024] Another aspect of the invention provides a system for automatically controlling a locomotion intensity of a human or other animal subject. The system comprises: one or more sensors for sensing one or more corresponding parameters of the locomotion movement of the subject and for generating therefrom a measured speed which represents an estimate of the subject's actual locomotion speed; one or more sensors for sensing one or more corresponding parameters correlated with an intensity indicator of the subject and for generating therefrom a measured intensity which represents an estimate of the subject's actual locomotion intensity; and a controller configured to: determine an intensity error comprising a difference between a desired intensity and the measured intensity; and if an absolute value of the intensity error is outside of a threshold region around the desired intensity: convert the desired intensity to a desired speed; determine a speed error comprising a difference between the desired speed and the measured speed; and output, to the subject, a speed-based stimulus frequency signal wherein the speed-based stimulus frequency signal is based on the speed error in such a manner that when the subject ambulates in a manner that matches a frequency of the speed-based stimulus frequency signal, the subject's actual intensity controllably tracks the desired intensity; and if the absolute value of the intensity error is within the threshold region around the desired intensity: output, to the subject, an intensity-based stimulus frequency signal wherein the intensity-based stimulus frequency signal is based on the intensity error in such a manner that when the subject ambulates in a manner that matches a frequency of the intensity-based stimulus frequency signal, the subject's actual intensity controllably tracks the desired intensity.

[0025] In addition to the exemplary aspects and embodiments described above, further aspects and embodiments will become apparent by reference to the drawings and by study of the following detailed descriptions.

BRIEF DESCRIPTION OF DRAWINGS

[0026] In drawings, which illustrate non-limiting embodiments of the invention:

[0027] FIG. 1A is a graphical depiction of plots which show experimentally determined correlation between stimulus fre-

quency (which is output to a subject via auditory tones and which the subject is instructed to match) and estimated running speed;

[0028] FIG. 1B is a schematic block diagram depiction of the experimental setup used to obtain the FIG. 1A plots;

[0029] FIG. 2 is a schematic block diagram depiction of a control system for automatically controlling human/animal running/walking speed according to a particular embodiment of the invention;

[0030] FIG. 3 is a schematic block diagram depiction of a controller of the FIG. 2 control system according to a particular embodiment of the invention;

[0031] FIG. 4 is a schematic block diagram depiction of a control system for automatically controlling human running/walking position according to a particular embodiment of the invention;

[0032] FIG. 5 is a schematic depiction of a number of reference speed profiles that could be generated by the FIG. 2 reference speed generator in response to user input;

[0033] FIG. 6 depicts one particular implementation of the FIG. 2 control system according to a particular embodiment;

[0034] FIG. 7 is a graphical depiction of plots which show the operation of the FIG. 6 implementation;

[0035] FIG. 8 is a schematic block diagram depiction of a control system for automatically controlling human running/walking intensity according to a particular embodiment of the invention; and

[0036] FIG. 9 is a graphical depiction of plots which show the operation of the FIG. 8 system for the control of locomotion intensity.

DESCRIPTION

[0037] Before the embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangements of the operative components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced or being carried out in various ways. Also, it is understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use herein of “including” and “comprising”, and variations thereof, is meant to encompass the items listed thereafter and equivalents thereof. Unless otherwise specifically stated, it is to be understood that steps in the methods described herein can be performed in varying sequences.

[0038] One may define the frequency of locomotion (e.g. running or walking) as the number of steps taken in a unit of time. Locomotion frequency may be measured in units of s^{-1} or Hz. When a human is running and/or walking, the human exhibits a high degree of correlation (e.g. a one-to-one mapping) between their locomotion frequency and speed—i.e. when instructed or otherwise caused or motivated to run at a particular frequency, humans and other animals automatically adjust their speed accordingly. When instructed or otherwise caused or motivated to run at a higher frequency, humans will tend to run faster. When instructed or otherwise caused or motivated to run at a lower frequency, humans will tend to run slower.

[0039] Particular embodiments of the invention provide methods and systems for automatic control of the locomotion (e.g. running or walking) speed of a human or other animal subject. The methods and systems involve estimating the subject's locomotion speed using one or more sensors, deter-

mining a difference (referred to as an error) between a desired speed and the estimated speed, and outputting (to the subject) a stimulus frequency wherein the output stimulus frequency is based on the error in such a manner that when the subject runs in a manner that matches the output stimulus frequency, the subject's actual speed tracks or matches the desired speed or otherwise tends to minimize the error. Other embodiments provide automatic control of human locomotion position (rather than speed). Systems and methods of particular embodiments, help the subject's locomotion speed and/or position automatically converge to, and stay at, desired speed and position parameters (e.g. speed and/or positions profiles).

[0040] Other aspects of the invention make use of the aforementioned methods and systems for automatic locomotive speed control to assist with automatic control of the intensity of locomotion (e.g. running or walking) of a human or other animal subject. In particular embodiments, speed control is used to control the subject's locomotion speed to cause the subject's locomotion intensity to move toward a desired intensity until the subject's locomotive intensity is within a threshold range around the desired intensity. Once the subject's locomotive intensity is within the threshold range around the desired intensity, the methods and systems switch to direct automatic intensity control. The subject's locomotive intensity is estimated using one or more intensity indicators, which may be measured or otherwise determined using one or more corresponding sensors. Within the threshold range around the desired intensity, direct automatic intensity control may be effected by: determining a difference (referred to as an intensity error) between the desired intensity and the estimated intensity, and outputting (to the subject) a stimulus frequency wherein the output stimulus frequency is based on the intensity error in such a manner that when the subject runs in a manner that matches the output stimulus frequency, the subject's actual intensity tracks or matches the desired intensity or otherwise tends to minimize the intensity error. Systems and methods of particular embodiments, help the subject's locomotion intensity automatically converge to, and stay at, desired intensity parameters (e.g. intensity profiles).

[0041] A basic and well understood principle that underlies our scientific understanding of neural control of human locomotion (e.g. running and walking) is that humans use a distinct step frequency for each speed. This relationship can also be inverted—i.e. when a human is instructed or otherwise caused or motivated to match locomotion frequency to a reference frequency, a distinct speed is selected, resulting in a high degree of correlation (e.g. a one-to-one relationship) between step frequency and locomotion speed.

[0042] FIG. 1A shows a pair of plots taken in a laboratory experiment which demonstrate the high degree of correlation in the relationship between the frequency at which a human is instructed to run (plot 10) and their resultant speed (plot 12). FIG. 1B is a schematic block diagram showing the experimental apparatus 20 giving rise to the FIG. 1A plots. As shown in FIG. 1B, a human subject 26 was instructed (instructions 24) to run in a manner which matched their step frequency to an auditory frequency stimulus 30 output (by a frequency generator 22, to subject 26) via a pair of headphones (not explicitly shown). Subject 26 ran on a 400 meter outdoor track and was free to choose their running speed (actual running speed 32). The actual running speed 32 of subject 26 was measured by a speed measurement device 28 to obtain estimated running speed 34. Estimated speed 34 sensed or otherwise detected by speed measurement device

28 may also be referred to herein as measured speed **34**. In the particular case of the experiment giving rise to the plots of FIG. 1A, speed measurement device **28** involved using gyroscopic sensors **28A**, **28B** coupled to the subject's feet, as discussed in more detail below (see FIG. 6).

[0043] For the exemplary plots of FIG. 1A, frequency generator **22** was programmed to output a frequency stimulus signal **30** which included a series of $n=4$ constant reference frequencies for $t=2$ minute each. The frequency output stimulus **30** of frequency generator **22** is shown in FIG. 1A as frequency plot **10** and the estimated speed **34** of subject **26** is shown in FIG. 1A as speed plot **12**. It can be seen from the FIG. 1A plots, that whenever a change in frequency **10** occurred, the runner automatically adjusted their speed **12**, even though they were only instructed to match the frequency and not specifically instructed to adjust their speed. In addition, the adjustments to the speed **12** occurred within a few seconds after each corresponding change in frequency **10**.

[0044] FIG. 2 is a schematic block diagram of a human running/walking speed control system **50** according to a particular embodiment. Like experimental system **20** of FIG. 1B, control system **50** comprises a frequency generator **22** for outputting a stimulus frequency **30** and a speed measurement device **28** for measuring the actual running/walking speed **32** of subject **26** and outputting a measured/estimated speed **34**. In particular embodiments, frequency generator **22** outputs an auditory frequency stimulus signal **30** which may be provided to subject **26** via a pair of headphones/ear buds or the like. It is envisaged, however, that in other embodiments, frequency generator **22** may provide the subject with additional or alternative forms of frequency stimulus **30** (e.g. optical and/or tactile frequency stimulus). In one currently implemented embodiment, speed measurement device **28** comprises gyroscopic sensors **28A**, **28B** coupled to the subject's feet, as discussed in more detail below (see FIG. 6), but it is envisaged that system **50** could make use of any suitable speed measurement device, such as any of those described herein.

[0045] Control system **50** incorporates a controller **52** which may be used to control measured speed **34** to track a desired speed (also referred to as a reference speed) **62**. Controller **52** may be implemented on or by one or more suitably configured data processors, personal computers, programmable logic devices and/or the like. Controller **52** may be implemented via one or more embedded data processors or micro-electronic devices to permit system **50** to be carried with subject **26** when they are running or walking. In the illustrated embodiment, reference speed **62** is generated by a reference speed generator **54** in response to user input **56**. Reference speed generator **54** may also be implemented on or by one or more suitably configured data processors, personal computers, programmable logic devices and/or the like which may be programmed with suitable user interface and speed generator software.

[0046] In the illustrated embodiment, reference speed generator **54** and controller **52** are implemented by the same hardware (e.g. one or more suitably programmed data processors) which is shown in dashed lines as control hardware **58**. Control hardware **58** may perform instructions in the form of suitably programmed software. In some embodiments, control hardware **58** may be implemented in the form of one or more embedded processors that can perform substantially all of the functionality of controller **52** and reference speed generator **54**. In some embodiments, control hardware **58** may interface with (e.g. plug into or wirelessly interface with)

a suitably programmed computer to accept user input **56** and then the remaining functions of controller **50** and/or reference speed generator **54**) may be implemented by a suitably programmed embedded processor. In still other embodiments, controller **52** and reference speed generator **54** can be implemented using separate hardware.

[0047] In some embodiments (although not specifically shown in FIG. 2), some of the functionality of speed measurement device **28** may also be implemented by control hardware **58**. For example, control hardware **58** may be configured to receive information from one or more sensors (e.g. gyroscopes, GPS sensors or the like) and may process or otherwise interpret this information to determine an estimated speed **34**. By way of a specific example, control hardware **58** may determine measured speed **34** by receiving two different position measurements from a position sensor (e.g. a GPS sensor) and dividing the two position measurements by an intervening time to obtain measured speed **34**. In some embodiments (although not specifically shown in FIG. 2), control hardware **58** may perform some (or even all) of the functionality of frequency generator **22**. For example, control hardware **58** could implement a portion of frequency generator **22** in the form a "count-down register" which outputs a pulse when it counts down from a specified period. This pulse could then be amplified and output to subject **26** via a pair of headphones or some other output device.

[0048] The operation of system **50** may be controlled by control hardware **58**. Referring to FIG. 2, system **50** compares measured locomotion speed **34** with user-defined reference speed **62**. System **50** generates an error signal **64** which comprises a difference between reference speed **62** and measured speed **34**. Based on error signal **64**, controller **52** outputs a control signal **60** which causes frequency generator **22** to change stimulus frequency **30** to minimize the speed error (i.e. error signal **64**). When measured speed **34** is below reference speed **62** (i.e. error signal **64** is positive), controller **52** will output a control signal **60** which causes frequency generator **22** to increase stimulus frequency **30**. Conversely, when measured speed **34** is above reference speed **62**, controller **52** will output a control signal **60** which causes frequency generator **22** to decrease stimulus frequency **30**. Subject **26** tends to synchronize, or can be instructed to synchronize, their movements to match stimulus frequency **30**. The change in stimulus frequency **30** will lead to a corresponding change in actual locomotion speed **32** because, as discussed above, humans and other animals prefer to use a particular running/walking speed for each specified frequency. The new actual speed **32** is detected by speed measurement device **28** which outputs a new measured speed **34** which is again compared to reference speed **62** to adjust stimulus frequency **30** if desired. Stimulus frequency **30** is continually or periodically changed until measured locomotion speed **34** equals reference speed **62**. System **50** thereby provides a feedback-based control system that controls actual running/walking speed **32** using a speed dependent stimulus frequency **30**.

[0049] FIG. 3 is a schematic block diagram depiction of controller **52** of the FIG. 2 control system **50** according to a particular embodiment of the invention. Controller **52** of the illustrated embodiment comprises a proportional-integral-derivative (PID) controller which receives error signal **64** and outputs a control signal **60** according to:

$$y(t) = k_p \cdot e(t) + k_d \frac{d}{dt} e(t) + k_i \int e(t) dt \quad (1)$$

where $y(t)$ represents the control signal **60**, $e(t)$ represents the error signal **64** and k_p , k_i , k_d respectively represent proportional gain **66**, integral gain **68** and derivative gain **70**. The integration and differentiation operators of equation (1) are respectively depicted as blocks **72**, **74** of the FIG. 3 schematic depiction. Not specifically shown in the FIG. 3 depiction is a mapping between the output of summing junction **76** and a control signal **60** that is suitable for input to frequency generator **22** (see FIG. 2). In one particular implementation, frequency generator **22** outputs a stimulus frequency that matches the stimulus frequency of control signal **60**. In such embodiments, a mapping may not be required between the output of summing junction **76** and control signal **60**. It will be appreciated that such a mapping will depend on the particular frequency generator **22** used for any given application.

[0050] The gain parameters k_p , k_i , k_d (blocks **66**, **68**, **70**) specify the relative contribution of the proportional, integral and derivative controller parts to control signal **60**. These gain parameters k_p , k_i , k_d (blocks **66**, **68**, **70**) can be adjusted (e.g. calibrated and/or experimentally determined) to optimize the controlled behavior of subject **26**. The gain parameters k_p , k_i , k_d (blocks **66**, **68**, **70**) may be user-configurable constants or may be functions of other parameters (e.g. time and/or speed). In some embodiments, one or more of the gain parameters k_p , k_i , k_d (blocks **66**, **68**, **70**) may be set to zero. In some embodiments, gain parameters k_p , k_i , k_d (blocks **66**, **68**, **70**) can be configured so that the changes in stimulus frequency **30** are not overly noisy or do not exhibit overly large jumps. In other embodiments, other control techniques may be used to obtain similar results. By way of non-limiting example, in addition to or in the alternative to using the first derivative (single differentiator **74**) and first integral (single integrator **72**) of error signal **64** as shown in FIG. 3, some embodiments may involve higher order derivatives and/or integrators of error signal **64** to determine control signal **60**.

[0051] FIG. 4 is a schematic block diagram of a human running/walking position control system **150** according to another particular embodiment. Position control system **150** is similar in many respects to speed control system **50** of FIG. 2, except that position control system **150** uses position (instead of speed) as the control variable.

[0052] Control system **150** comprises a frequency generator **122** which outputs a stimulus frequency **130** in response to control signal **160**. Frequency generator **122** may be substantially similar to frequency generator **22** of system **50**. Instead of a speed measurement device, position control system **150** comprises a position measurement device **128** which outputs a measured position **134** (also referred to as an estimated position **134**) of subject **126**. It will be appreciated that in some embodiments, position measurement device **128** of position control system **150** may be implemented by integrating the measured speed output of a speed measurement device (e.g. measured speed output **34** of speed measurement device **28** of speed control system **50**). Similarly, speed measurement device **28** of speed control system **50** could be implemented by differentiating the measured position output of a position measurement device (e.g. measured position output **134** of position measurement device **150** of position control system **150**).

[0053] Position control system **150** comprises controller **152** and reference position generator **154** which may be similar to controller **52** and reference speed generator **54** of speed control system **50**. In particular, controller **152** and reference position generator **154** may be implemented in any of manners discussed above for controller **52** and reference speed generator **54**. In the illustrated embodiment, controller **152** and reference position generator **154** are implemented by control hardware **158**.

[0054] The operation of system **150** may be controlled by control hardware **158**. Referring to FIG. 4, system **150** compares measured locomotion position **134** with user-defined reference position **162**. Reference position **162** may comprise a reference trajectory and/or a desired position **162** for any given time or any other suitable position information. System **150** generates an error signal **164** which comprises a difference between reference position **162** and measured position **134**. Based on error signal **164**, controller **152** outputs a control signal **160** which causes frequency generator **122** to change stimulus frequency **130** to attempt to minimize the position error (i.e. error signal **164**). When measured position **134** is behind a desired reference position **162** (i.e. error signal **164** is positive), controller **152** will output a control signal **160** which causes frequency generator **122** to increase stimulus frequency **130** with the objective of reducing position error **164** over time. Conversely, when measured position **134** has advanced beyond a desired reference position **162**, controller **152** will output a control signal **160** which causes frequency generator **122** to decrease stimulus frequency **130** with the objective of reducing position error **164** over time. Subject **26** tends to synchronize, or can be instructed to synchronize, their movements to match stimulus frequency **130**. The change in stimulus frequency **130** will lead to a corresponding change in actual locomotion speed (not shown in FIG. 4) because, as discussed above, humans and other animals prefer to use a particular running/walking speed for each specified frequency. After this speed adjustment, a resultant position **132** is detected by position measurement device **128** which outputs a new measured position **134** which is again compared to reference position **162** to adjust stimulus frequency **130** if desired. Stimulus frequency **130** is continually changed until measured locomotion position **134** equals reference position **162**. System **150** thereby provides a feedback system that controls actual running/walking position **132** using a position dependent stimulus frequency **130**.

[0055] Controller **152** of system **150** may also be implemented by a PID control scheme similar to that shown schematically in FIG. 3, except that error signal **164** represents a position error in the case of controller **152** (rather than a speed error, as is the case in controller **52** of FIGS. 2 and 3).

[0056] FIG. 8 is a schematic block diagram of a human running/walking intensity control system **250** according to another particular embodiment. As mentioned above, locomotive intensity is typically estimated using one or more estimatable or measurable intensity indicators which may include, by way of non-limiting example, hear rate, metabolic rate, oxygen consumption, perceived exertion, mechanical power and/or the like. In the illustrated embodiment, control system **250** uses the heart rate of subject **226** as an intensity indicator, but this is not necessary. In other embodiments, other additional or alternative intensity indicators could be used. Intensity control system **250** is similar in some respects to speed control system **50** of FIG. 2, except that intensity control system **250** uses both speed and intensity (as reflected

in the heart rate of subject 226 which is used as an intensity indicator) as control variables. As described in more detail below, intensity control system 250 uses speed control to achieve a number of advantages over intensity control alone.

[0057] Control system 250 comprises a frequency generator 222 which outputs a stimulus frequency 230 in response to control signal 260. Frequency generator 222 may be substantially similar to frequency generator 22 of system 50. Control system comprises a speed measurement device 228 which may be substantially similar to speed measurement device 28 of system 50 and which senses actual speed 232 of subject 226 and outputs a measured speed 234 (also referred to as an estimated speed 234) of subject 226. In addition to speed measurement device, system 250 comprises a heart rate measurement device 288 which senses actual heart rate 290 of subject 226 and outputs a measured heart rate 284 (also referred to as an estimated heart rate) of subject 226.

[0058] Intensity control system 250 also comprises a reference heart rate generator 254 which may be similar to reference speed generator 54 of speed control system 50. In particular, reference heart rate generator 254 may be implemented in any of manners discussed above for reference speed generator 54. In the illustrated embodiment, reference heart rate generator 254 is implemented by control hardware 258. Reference heart rate generator 254 outputs a reference heart rate 262 and intensity control system 250 attempts to cause the actual heart rate 290 of subject 226 to track the reference heart rate 262. Reference heart rate generator 254 may output reference heart rate 262 in response to user input 256.

[0059] Intensity control system 250 comprises a controller 252 which may be similar to controller 52 of speed control system 50. In the illustrated embodiment, controller 252 is implemented by the same control hardware 258 as reference heart rate generator 254. For the purposes of the schematic illustration of FIG. 8, controller 252 is shown to comprise a speed controller 252A, a heart rate controller 252B and a control region switch 286. As will be discussed in more detail below, speed controller 252A effects speed control in a manner similar to that discussed above for speed control system 50, heart rate controller 252B effects heart rate control and control region switch 286 switches system 250 between heart rate control and speed control. It will be appreciated, especially in view of the description to follow, that in practice, speed controller 252A, heart rate controller 252B and control region switch 286 may be implemented by the same logic (e.g. a suitably programmed processor or the like).

[0060] Intensity control system 250 also comprises a reference speed predictor 280 which receives, as input, reference heart rate signal 262 and outputs a corresponding reference speed 281. Reference speed predictor 280 may be implemented on or by one or more suitably configured data processors, personal computers, programmable logic devices and/or the like which may be programmed with suitable user interface and speed generator software. In the illustrated embodiment, reference speed predictor 280 is implemented by the same control hardware 258 as reference heart rate generator 254 and controller 252.

[0061] In converting an input reference heart rate signal 262 into an output reference speed signal 281, reference speed predictor 280 may be configured to implement a model which maps human (or animal) heart rate to locomotive speed. Such models are well known in the art and include, by way of non-limiting example, the model proposed by Her-

mansen L. & Saltin B (1969), Oxygen uptake during maximal treadmill and bicycle exercise. *Journal of Applied Physiology*, 26: 31-37 which is hereby incorporated herein by reference. Reference speed predictor 280 may incorporate or consider subject specific data (e.g. calibration data). Such subject specific data may be incorporated into the heart rate to locomotive speed mapping model implemented by reference speed predictor 280 or may otherwise be incorporated into the heart rate to locomotive speed conversion algorithms of reference speed generator 280. Such subject specific calibration data may comprise one or more simultaneous measurements of heart rate and locomotive speed for subject 226—for example, subject 226 may run on a track and their locomotive speed and heart rate may be simultaneously measured at one or more times.

[0062] In one particular embodiment, subject specific calibration data may be used in the following manner. Once one or more simultaneous measurements of heart rate and locomotive speed are obtained for subject 226, as described above, the heart rate to locomotive speed mapping model is used to calculate a model-predicted locomotive speed at the heart rates measured during calibration. These model-predicted speeds may be compared to the measured speeds to generate corresponding model errors. Some sort of average may be taken of these model errors and this average model error may be used by reference speed generator 280 to predict an output reference speed signal 281 from reference heart rate signal 262. More particularly, the result of the heart rate to locomotive speed mapping model may be offset by the average model error to obtain output reference speed 281.

[0063] In another particular embodiment, the heart rate to locomotive speed mapping model may itself be calibrated with subject specific calibration data. For example, subject 226 may go on a specific calibration run, which may guide subject 226 through a series of speeds while measuring the corresponding heart rate at each speed. Still another alternative involves using historical data from previous work-outs (e.g. from previous uses of system 250) to find instances when the heart rate of subject 226 is in a steady state and to record the corresponding locomotive speeds. Such use of historical data may be able to work without pre-calibration and may be constantly updated based on the present fitness status of subject 226. If enough user specific calibration data is collected, then reference speed generator 280 may use this user specific calibration data without having to rely on a heart rate to locomotive speed mapping model.

[0064] In practice, either or both of the heart rate to locomotive speed mapping model and the user specific calibration data used by reference speed generator 280 may be stored in a look up table or the like in accessible memory (not shown) which may be part of control hardware 258.

[0065] In operation, intensity control system 250 controls the locomotive intensity of subject 226 (as indicated, in the illustrated embodiment, by the heart rate of subject 226 which represents one or many possible intensity indicators which could be used by system 250). Although locomotion speed and intensity are highly correlated, external disturbances like wind and/or terrain changes, and internal disturbances such as fatigue, influence the relationship between locomotion speed and intensity. Locomotion intensity control system 250 leverage speed control (as implemented by speed control portion 250A) to assist heart rate control portion 250B to accurately control locomotive intensity (heart rate).

[0066] In theory, heart rate control portion 250B could be implemented without the use of additional speed control portion 250A to effect heart rate control—e.g. heart rate controller 252B could output a heart rate control signal 285 which would become an input signal 260 to frequency generator 222 and which would cause frequency generator 222 to output a stimulus frequency 230 which, when followed by subject 226, minimizes the heart rate error 282 between reference heart rate 262 and the measured heart rate 284 of subject 226. If, for example, measured heart rate 284 is below reference heart rate 262, heart rate controller 252B would output a heart rate control signal 285 which would cause frequency generator 222 to increase stimulus frequency 230 to cause a corresponding increase in the speed of subject 226 which in turn would increase the actual and measured heart rate 290, 284 of subject 226.

[0067] However, heart rate dynamics are slow. Physiological research has determined that after a change in locomotion speed, it may take several minutes for the heart rate to reach a steady state corresponding to the new locomotive speed. As a result of these slow heart rate dynamics, controlling heart rate based purely on the difference between a reference heart rate (e.g. reference heart rate 262) and a measured heart rate (e.g. measured heart rate 284) can be problematic. For example, if a user's measured heart rate is below the reference heart rate, the controller will increase the stimulus frequency to minimize the heart rate error. In response to this increased stimulus frequency, the user will increase his or her locomotive speed. However, because it takes time for the user's heart rate to reach a steady state value corresponding to this new speed, the controller will continue to increase the stimulus frequency. Typically, this will result in overshoot and/or oscillation of the reference heart rate (and corresponding overshoot and/or oscillation of speed) because the user's speed is increased beyond the speed that would result in the reference heart rate. These issues are the most apparent when there is a large initial error between the reference and measured heart rates.

[0068] These issues may be overcome to some degree by suitable selection of control parameters, but the resulting control is undesirably slow. These issues may also be overcome to some degree by controlling heart rate relatively loosely—e.g. by accepting actual heart rates that are within a large margin of error with respect to the reference heart rate. These potential solutions do not allow for accurate and rapid control of the heart rate.

[0069] Intensity control system 250 of the illustrated embodiment overcomes this issue by leveraging speed control (implemented by speed control portion 250A) to bring measured heart rate 284 close to reference heart rate 262 (e.g. within a threshold region around reference heart rate 262) and limiting the use of heart rate control (implemented by heart rate control portion 250B) to provide fine adjustment once measured heart rate 284 of subject 226 is close to reference heart rate 262 (e.g. within the threshold region around reference heart rate 262). The threshold region around reference heart rate 262 may be a user-configurable parameter of system 250 or may be a predefined parameter of system 250. The threshold region around reference heart rate 262 may be defined in a number of different ways. By way of non-limiting example, the threshold region may be specified to be the reference heart rate $\pm x$ beats per minute or the reference heart rate $\pm x$ % of the reference heart rate, where x may be a user-configurable threshold region parameter.

[0070] If measured heart rate 284 is outside of the threshold region around reference heart rate 262, then control system 250 will use speed control portion 250A which may be considered (in the schematic depiction of FIG. 8) to mean that control region switch 286 is configured to connect speed control signal 287 from speed controller 252A to input 260 of frequency generator 222. It will be appreciated by those skilled in the art, that control region switch 286 may not be physically present as a switch and may be implemented (e.g. in software) by controller 252. Speed control portion 250A of system 250 attempts to output a stimulus frequency 230 which will cause subject 226 to increase or decrease their locomotive speed so as to move their actual and measured heart rates 290, 284 toward reference heart rate 262. Speed control portion 250A uses reference speed predictor 280 discussed above to convert reference heart rate 262 into a reference speed 281. Once this reference speed 281 is obtained, the operation of speed control portion 250A of system 250 is substantially similar to the operation of speed control system 50 described above, while measured heart rate 284 is outside the threshold region around reference heart rate 262.

[0071] Controller 252 may monitor the heart rate error signal 282 (which reflects the difference between measured heart rate 284 and reference heart rate 262). Once heart rate error signal 282 is sufficiently small (i.e. measured heart rate 284 is within the threshold region around reference heart rate 262), system 250 switches to heart rate control. This may be considered (in the schematic depiction of FIG. 8) to mean that control region switch 286 switches to connect heart rate control signal 285 from heart rate controller 252B to input 260 of frequency generator 222. Thereafter, intensity control system effects control of heart rate. In some embodiments, if the heart rate error 282 goes outside of the threshold region around reference heart rate 262, then control system 250 may switch back to speed control, but this is not necessary. In some embodiments, control system 250 may also switch from speed control to heart rate control in other circumstances. By way of non-limiting example, control system 250 may switch from speed control to heart rate control if speed control does not bring measured heart rate 284 to within the threshold region around reference heart rate 262 within a threshold period of time. Such a threshold period of time may be a user-configurable parameter.

[0072] The operation of control system 250 in heart rate control mode (e.g. the operation of heart rate control portion 250B) may be similar to the various control systems described above. Referring to FIG. 8, heart rate control portion 250B compares measured heart rate 284 with user-defined reference heart rate 262. Reference heart rate 262 may comprise a reference trajectory and/or a desired heart rate 262 for any given time or any other suitable heart rate information. Heart rate control portion 250B generates a heart rate error signal 282 which comprises a difference between reference heart rate 262 and measured heart rate 284. Based on heart rate error signal 282, heart rate controller 252B outputs a heart rate control signal 285 which is received by frequency generator 222 as input signal 260 and which causes frequency generator 222 to change stimulus frequency 230 with the objective of minimizing heart rate error 282. When measured heart rate 284 is below a desired reference heart rate 262 (i.e. heart rate error signal 282 is positive), heart rate controller 252B will output a heart rate control signal 285 which causes frequency generator 222 to increase stimulus frequency 230 with the objective of reducing heart rate error 282 over time.

Conversely, when measured heart rate **284** is greater than a desired reference heart rate **262**, heart rate controller **252B** will output a heart rate control signal **285** which causes frequency generator **222** to decrease stimulus frequency **230** with the objective of reducing heart rate error **282** over time. Subject **226** tends to synchronize, or can be instructed to synchronize, their movements to match stimulus frequency **230**. The change in stimulus frequency **230** will lead to a corresponding change in actual locomotion speed **232** because, as discussed above, humans and other animals prefer to use a particular running/walking speed for each specified frequency. After this speed adjustment, a resultant heart rate is detected by heart rate measurement device **288** which outputs a new measured heart rate **284** which is again compared to reference heart rate **262** to adjust stimulus frequency **230** if desired. Stimulus frequency **230** is continually changed until measured heart rate **284** equals reference heart rate **262**. System **250** thereby provides a feedback system that controls actual heart rate **290** using a heart rate dependent stimulus frequency **230**.

[0073] The profile of a reference speed **62** (and the corresponding user input **56** to reference speed generator **154**), the profile of a reference position **162** (and the corresponding user input **156** to reference position generator **154**) and/or the profile of a reference heart rate **262** (and the corresponding user input **256** to reference heart rate generator **254**) may take a variety of forms. By way of non-limiting example, in the case of speed control, a user may specify:

[0074] the total time to cover a certain distance (e.g. 50 min for a 10 km race). The user may also specify that the distance is to be run at a constant speed or that the speed should have some profile (e.g. starting a relatively high speed, stepping down slightly to a middle speed and then increasing for a “kick” at the end of the race).

[0075] an interval training regime, which will guide the subject through a series of predetermined or user-configurable speeds (e.g. 5 min at 3 m/s, 2 min at 3.5 m/s, 1 min at 4 m/s etc. or 2 km at 3 m/s, 1 km at 3.5 m/s, 1 km at 4 m/s, etc.).

[0076] a training or race profile that increases speed when only a certain amount of time or distance remains.

[0077] a completely user-configurable profile for training or racing purpose; and/or

[0078] the like.

[0079] In addition to or in the alternative to a user inputting a training or race profile, such a profile could be input by a real or virtual trainer. The training or race profile can also be changed on the fly by the user or trainer changing reference speed **62** or position **162** or heart rate **262**. It is also possible for a user to download data (e.g. another person’s speed profile data from the other person’s workout at a distant place and/or time). A training or race profile based on this data can then be input so that the user can virtually train with, or race against, this other person.

[0080] FIG. 5 schematically depicts a number of exemplary and non-limiting speed profiles (i.e. profiles for desired/reference speed **62**) including constant speed profile **200**, interval speed profile **202** and ramping speed profile **204**. It will be appreciated that position and/or heart rate profiles similar to any of the above-discussed speed profiles could be generated by reference position generator **154** in response to user input **156** and/or by heart rate generator **254** in response to user input **256**.

[0081] Speed measurement device **28** can be implemented using a variety of different techniques and speed measurement apparatus. A number of technologies capable of measuring running/walking speed are discussed above. Various different sensors may be used, individually or combined with other sensors, to implement such speed measurement apparatus. By way of non-limiting example, signals from accelerometers, GPS, gyroscopes, optical and electromagnetic sensors can be processed to provide locomotion speed and information. Various processing techniques may be used to extract speed and/or position information from such sensors. The particular nature of the processing depends on the type of sensors used. Signals from such sensors may be combined with one another in an attempt to improve the accuracy of estimated speed **34**. Such sensor combination can involve state estimation techniques such as Kalman-filtering, for example. Similarly, position measurement device **128** can be implemented using a variety of different techniques and position measurement apparatus. For some speed or position measurement devices **28**, **128**, a calibration procedure might be desirable, whereas other speed or position measurement devices **28**, **128** could provide accurate speed or position estimates **34**, **134** without user calibration. Heart rate measurement device **288** can similarly be implemented using a variety of techniques known in the art, such as strapped and/or strapless heart rate measurement systems.

[0082] Stimulus frequency **30**, **130**, **230** can be output to subject **26**, **126**, **226** in a variety of ways and may target different sensory systems of subject **26**, **126**, **226**. One particular embodiment, makes use of an auditory metronome which outputs an auditory frequency stimulus signal **30**, **130**, **230** to subject **26**, **126**, **226**. Another implementation using auditory signals involves the use of music as frequency stimulus **30**, **130**, **230**. For example, the frequency (tempo) of music could be controlled so that either songs with the right frequency are selected, or the frequency of a song is adjusted to better match the intended locomotion frequency. Frequency stimulus **30**, **130**, **230** could also be implemented as a tactile stimulus, either by mechanical or electrical stimulation to different body parts (heel, back, arm, wrist etc.). Also, frequency stimulus **30**, **130**, **230** could be provided visually, for example by projecting it on the inside of a pair of glasses or in some other location visible to subject **26**, **126**, **226**.

[0083] Control signals **60**, **160**, **285**, **287** (and corresponding stimulus frequency **30**, **130**, **230**) can be updated whenever estimated speed/position/heart rate **34**, **134**, **234**, **284** is updated and may be accomplished, in one particular example, by continually changing the frequency of a metronome or the tempo of a song. Such relatively short control periods may occur, for example, in time periods on the order of tens of milliseconds. In some situations, it might be more comfortable for the subject if control signal **60**, **160**, **285**, **287** (and corresponding stimulus frequency **30**, **130**, **230**) were only updated at longer control intervals. Such longer control periods may be on the order seconds, tens of seconds or even minutes. Such control periods may not be temporally constant—for example when music is used as stimulus frequency **30**, **130**, **230** a control period may correspond to the length of a particular song and an update to control signal **60** (and stimulus frequency **30**) can be provided each time that a new song is selected.

[0084] In such embodiments, controller **52**, **152**, **252** may establish a relationship between stimulation frequency **30**, **130**, **230** and subject-specific locomotion speed and/or heart

rate. Such a relationship may be used to predict the locomotion speed or heart rate that subject 26, 126, 226 is likely to adopt when a certain song is played. This relationship between stimulation frequency and locomotion speed or heart rate can be calibrated on a subject specific basis. For example, the relationship between stimulation frequency and locomotion speed or heart rate may be calibrated using a speed interval regime, where subject 26, 126, 226 is guided through a number of different speeds. Control signals 60, 160, 285, 287 could also only be played when the measured speed, position or heart rate is outside a threshold range (e.g. a user configurable threshold range), in order to return subject 26, 126, 226 to the reference speed, position or heart rate. Current estimated step frequency may be used as the initial value for stimulus frequency 30, 130, 230. This frequency will then be adjusted by the control system to return subject 26, 126, 226 to the target speed, position or heart rate.

[0085] FIG. 6 depicts one particular implementation 300 of a control system 50 according to a particular embodiment. In the FIG. 6 implementation 300, a suitably programmed tablet personal computer (not shown), which may be carried by subject 26 in a backpack, is used to implement reference speed generator 54, a speed detection algorithm (not shown) used by speed measurement device 28 and controller 52. In the FIG. 6 implementation 300, controller 52 also performs the function of frequency generator 22 (see FIG. 2). Speed measurement device 28 comprises a pair of gyroscopes 28A, 28B attached to the feet of subject 26. Frequency stimulus 30 is provided to subject 26 via a pair of headphones for auditory stimulation (e.g. as a metronome).

[0086] The FIG. 6 implementation uses foot-mounted gyroscopes 28A, 28B to sense the running speed of subject 26. Gyroscopes 28A, 28B generate corresponding gyroscope sensor signals 29A, 29B. As is known in the art, gyroscope sensor signals 29A, 29B exhibit characteristic events that permit robust detection of foot touchdown and lift-off. By processing gyroscope signals 29A, 29B and identifying these events, speed measurement device 28 determines an estimate of the amount of time each foot spends on the ground during each step (contact time). This contact time information, in combination with a predetermined relationship between contact time and running speed, provides estimated speed 34. In some embodiments, estimated speed 34 may be determined as the moving average of the speed estimates over the previous number (e.g. two) steps. Those skilled in the art will recognize that this implementation of speed measurement device 28 represents one particular embodiment and that there are a variety of additional or alternative techniques for generating estimated running/walking speed 34.

[0087] Controller 52 of the FIG. 6 implementation 300 makes use of a discrete PID control scheme of the type shown schematically in FIG. 3 to control the running speed of subject 26. Estimated running speed 34 is compared to reference speed 62 to find error signal 64. Error signal 64 is sent to the different branches of controller 52 to implement the control scheme of FIG. 3 and equation (1). In the current embodiment, the gain parameters k_p , k_i , k_d (blocks 66, 68, 70) are constant. Controller 52 of the FIG. 6 implementation 300 incorporates a frequency generator. Consequently, controller 52 outputs an updated stimulus frequency 30 in the form an auditory stimulus which is delivered to subject 26 via the illustrated earphones. In the current embodiment, stimulus frequency 30 is updated at each control step.

[0088] FIG. 7 is a graphical depiction of plots which show the operation of the FIG. 6 implementation. More particularly, FIG. 7 includes plot 314 of desired/reference speed 62 output by reference speed generator 54, plot 310 of auditory stimulus frequency 30 output by controller 52 and plot 312 of the estimated speed 34 of subject 26 as estimated by speed measurement device 28. The FIG. 7 data was once again obtained by having subject 26 run on a 400 meter outdoor track. Subject 26 was instructed to try to match their step frequency to the auditory stimulus frequency 30, but was free to choose their running speed. Reference speed generator 54 was programmed to guide subject through a speed interval regime incorporating a series of $n=4$ constant reference speeds 62 for $t=2$ minute each. Plots 312 and 314 show that estimated speed 34 of subject 26 converges rapidly toward each reference speed 62 and, on average, stayed at that reference speed 62 until the reference speed 62 changed again.

[0089] FIG. 9 is a graphical depiction of plots which show the operation of the FIG. 8 intensity control system 250. More particularly, FIG. 9 includes plots of desired/reference heart rate 262, a plot of the auditory stimulus frequency 230 and a plot of measured heart rate 284 of subject 226 as given by heart rate measurement device 288. The FIG. 9 data was once again obtained by having subject 226 run on a 400 meter outdoor track. Subject 226 was instructed to try to match their step frequency to auditory stimulus frequency 230, but was free to choose their running speed. Reference heart rate generator 254 was programmed to keep subject 226 at a constant heart rate of 160 beats per minute (bpm). FIG. 9 shows that measured heart rate 284 converged to reference heart rate 262 and then stayed at reference heart rate 262. Under speed control (the grey-colored region of FIG. 9), measured heart rate 284 climbs quickly up to a region of reference heart rate 262 without overshoot (although in some instances there may be some overshoot). Once measured heart rate 284 reaches a region close to reference heart rate 262, the control switches to intensity control and measured heart rate 284 tracks reasonably close to reference heart rate 262.

[0090] Variations and modifications of the foregoing are within the scope of the present invention. It is understood that the invention disclosed and defined herein extends to all the alternative combinations of two or more of the individual features mentioned or evident from the text and/or drawings. All of these different combinations constitute various alternative aspects of the present invention. The embodiments described herein explain the best modes known for practicing the invention. Aspects of the invention are to be construed to include alternative embodiments to the extent permitted by the prior art. For example:

[0091] It will be appreciated that the above-described PID control schemes represent one particular control scheme for implementing speed and/or position control of human walking/running according to one particular embodiment. Other embodiments may incorporate other control schemes. Such other control schemes may also be based on the error between desired speed and/or position and estimated speed and/or position. Such other control schemes may also be based on controlling a stimulus frequency output to the subject.

[0092] The control systems described above are representative examples only. Control systems in other embodiments could be modified to be more adaptive. For example, control systems could be designed to adaptively and dynamically adjust reference speed 62 (or

reference position 162 or reference heart rate 262) in response to feedback information. By way of non-limiting example, such feedback information could comprise current and historical values for estimated speed 34, 234 and/or estimated position 134 and/or estimated heart rate 284 and/or derivatives, integrals or other functions of these values. In one example, user input 56, 156 could specify that subject 26, 126 would like to cover 10 km in 50 minutes. A dynamic speed/position controller could then help to guide subject 26, 126 toward the appropriate speed/position to establish this objective by updating reference speed/position 62, 162 and minimizing error 64, 164 to achieve this objective. If, for some reason, subject 26, 126 is unable to keep up with to desired speed/position 62, 162, the controller might detect this and decide to slow down desired speed/position 62, 162 temporarily. When subject 26, 126 is able to keep up again, the controller could decide to increase the desired speed/position 62, 162 again, in order to get closer to the original objective. Additionally or alternatively, control systems could adaptively modify gain parameters of controller 52, 152, 252 (e.g. k_p , k_v , k_d) (blocks 66, 68, 70) to improve performance of the control system, such as, by way of non-limiting example, by adjusting rise times, adjusting settling times and/or overshoot.

[0093] As is known in the art, humans have the tendency to synchronize their movements to external stimuli, even when not explicitly instructed to do so. Consequently, it may not be necessary to instruct or train subject 26, 126, 226 to match external frequency stimulus 30, 130, 230—this entrainment may happen naturally.

[0094] Applications of this invention are not limited strictly to walking and running. Various embodiments may be directed toward other locomotion activities (e.g. snowshoeing, cross-country skiing, speed skating, inline skating and/or the like) and/or other activities involving cyclic movements (e.g. swimming, cycling, wheel chair racing and/or the like).

[0095] The above description relates to human subjects. However, the invention is not limited to application to humans. Particular embodiments of the invention may have application to other animals, including, for example, horses, dogs and/or other animals used for racing.

[0096] Control systems of particular embodiments may be used for rehabilitation of patients with various diseases or injuries affecting locomotion ability, including but not limited to stroke patients, Parkinson's patients, patients having spinal cord injuries, amputees, etc.

[0097] In the description above, intensity control system 250 is described in terms of a particular intensity indicator—i.e. heart rate. Heart rate is one of a variety of possible intensity indicators which may be used alone or in combination to effect intensity control in a manner analogous to that of control system 250. References to heart rate in the description above should be understood to incorporate the possibility of using other intensity indicator(s). Similarly references to components or features of control system that reference heart rate (e.g. heart rate measurement device 288, measured heart rate signal 284, heart rate controller 252B, etc.) should be understood to include the possibility of other intensity indicator(s)

1. A method for the automatic control of locomotion speed in a human or other animal subject, the method comprising: estimating the subject's actual locomotion speed using one or more sensors to thereby obtain a measured speed; determining an error comprising a difference between a desired speed and the measured speed; and outputting, to the subject, a stimulus frequency signal wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual speed controllably tracks the desired speed.

2. A method according to claim 1 wherein outputting the stimulus frequency signal based on the error comprises implementing a proportional-integral-derivative (PID) control scheme.

3. A method according to claim 2 wherein implementing the PID control scheme comprises generating a control signal based on the error and using the control signal as an input to a frequency generator which outputs the stimulus frequency signal in response to the control signal.

4. A method according to claim 1 wherein outputting the stimulus frequency signal based on the error comprises determining a first control term proportional to the error which is used, at least in part, to determine the stimulus frequency signal.

5. A method according to claim 4 wherein outputting the stimulus frequency signal based on the error comprises determining a second control term proportional to a time integral of the error which is used, at least in part, to determine the stimulus frequency signal.

6. A method according to claim 4 wherein outputting the stimulus frequency signal based on the error comprises determining a third control term proportional to a time derivative of the error which is used, at least in part, to determine the stimulus frequency signal.

7. A method according to claim 4 wherein outputting the stimulus frequency signal based on the error comprises generating a control signal as a combination of available control terms and using the control signal as an input to a frequency generator which outputs the stimulus frequency signal in response to the control signal.

8. A method according to claim 7 comprising updating the control signal with a control period of less than 10 seconds.

9. A method according to claim 7 comprising updating the control signal with a control period of less than 1 second.

10. A method according to claim 7 wherein the stimulus frequency signal is provided to the subject in a form of music and the control signal is updated at a conclusion of each musical piece.

11. A method according to claim 1 wherein the stimulus frequency signal comprises an auditory signal that is output to the subject.

12. A method according to claim 1 wherein the stimulus frequency signal comprises one or more of: a tactile signal that is output to the subject and a visual signal that is output to the subject.

13. A method according to claim 1 wherein the desired speed comprises a user-specified speed profile.

14. A method according to claim 13 wherein the user-specified speed profile comprises an interval profile which comprises a plurality of intervals with each interval comprising at least one of: a desired speed level for a desired period of time; and a desired speed level for a desired distance.

15. A method according to claim 13 wherein the user-specified speed profile comprises a ramping speed profile which includes one or more time periods when the desired speed is increasing constantly with time.

16. A method according to claim 13 wherein the user-specified speed profile comprises a profile downloaded from a communication network.

17. A method for the automatic control of locomotion position of a human or other animal subject, the method comprising:

estimating the subject's actual locomotion position using one or more sensors to thereby obtain a measured position;

determining an error comprising a difference between a desired position and the measured position; and

outputting, to the subject, a stimulus frequency signal wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual position controllably tracks the desired position.

18.-32. (canceled)

33. A method for the automatic control of locomotion intensity in a human or other animal subject, the method comprising:

estimating the subject's actual locomotion intensity using one or more sensors to thereby obtain a measured intensity;

determining an intensity error comprising a difference between a desired intensity and the measured intensity; and

if an absolute value of the intensity error is outside of a threshold region around the desired intensity:

estimating the subject's actual locomotion speed using one or more sensors to thereby obtain a measured speed;

converting the desired intensity to a desired speed;

determining a speed error comprising a difference between the desired speed and the measured speed; and

outputting, to the subject, a speed-based stimulus frequency signal wherein the speed-based stimulus frequency signal is based on the speed error in such a manner that when the subject ambulates in a manner that matches a frequency of the speed-based stimulus frequency signal, the subject's actual intensity approximately controllably tracks the desired intensity; and

if the absolute value of the intensity error is within the threshold region around the desired intensity:

outputting, to the subject, an intensity-based stimulus frequency signal wherein the intensity-based stimulus frequency signal is based on the intensity error in such a manner that when the subject ambulates in a manner that matches a frequency of the intensity-based stimulus frequency signal, the subject's actual intensity controllably tracks the desired intensity.

34. A method according to claim 33 wherein outputting the speed-based stimulus frequency signal based on the speed error comprises implementing a proportional-integral-derivative (PID) control scheme.

35. A method according to claim 34 wherein implementing the PID control scheme comprises generating a speed-based control signal based on the speed error and using the speed-

based control signal as an input to a frequency generator which outputs the speed-based stimulus frequency signal in response to the speed-based control signal.

36. A method according to claim 35 comprising updating the speed-based control signal with a speed-based control period of less than 10 seconds.

37. A method according to claim 35 comprising updating the speed-based control signal with a speed-based control period of less than 1 second.

38. A method according to claim 35 wherein the speed-based stimulus frequency signal is provided to the subject in a form of music and the speed-based control signal is updated at a conclusion of each musical piece.

39. A method according to claim 33 wherein outputting the intensity-based stimulus frequency signal based on the intensity error comprises implementing a proportional-integral-derivative (PID) control scheme.

40. A method according to claim 39 wherein implementing the PID control scheme comprises generating an intensity-based control signal based on the intensity error and using the intensity-based control signal as an input to a frequency generator which outputs the intensity-based stimulus frequency signal in response to the intensity-based control signal.

41. A method according to claim 40 comprising updating the intensity-based control signal with an intensity-based control period of less than 10 seconds.

42. A method according to claim 40 comprising updating the intensity-based control signal with an intensity-based control period of less than 1 second.

43. A method according to claim 40 wherein the intensity-based stimulus frequency signal is provided to the subject in a form of music and the intensity-based control signal is updated at a conclusion of each musical piece.

44. A method according to claim 33 wherein the speed-based stimulus frequency signal and the intensity-based stimulus frequency signal comprise an auditory signal that is output to the subject.

45. A method according to claim 33 wherein the speed-based stimulus frequency signal and the intensity-based stimulus frequency signal comprise one or more of: a tactile signal that is output to the subject and a visual signal that is output to the subject.

46. A method according to claim 33 wherein the desired intensity comprises a user-specified intensity profile.

47. A method according to claim 46 wherein the user-specified intensity profile comprises an interval profile which comprises a plurality of intervals with each interval comprising at least one of: a desired intensity level for a desired period of time; and a desired intensity level for a desired distance.

48. A method according to claim 46 wherein the user-specified intensity profile comprises a ramping intensity profile which includes one or more time periods when the desired intensity is increasing constantly with time.

49. A method according to claim 46 wherein the user-specified intensity profile comprises a profile downloaded from a communication network.

50. A method according to claim 33 wherein the threshold region around the desired intensity is defined to comprise an absolute intensity range around the desired intensity.

51. A method according to claim 50 wherein the locomotion intensity is reflected by one or more intensity indicators which comprise a heart rate of the subject and the absolute intensity range comprise a desired heart rate $\pm x$, where x is a beat rate parameter.

52. A method according to claim **51** wherein the beat rate parameter x is user-configurable.

53. A method according to claim **33** wherein the threshold region around the desired intensity is defined to comprise a percentage intensity range around the desired intensity.

54. A method according to claim **53** wherein the locomotion intensity is reflected by one or more intensity indicators which comprise a heart rate of the subject and the absolute intensity range comprise a desired heart rate $\pm x$, where x is a percentage parameter.

55. A method according to claim **54** wherein the percentage parameter x is user-configurable.

56. A method according to claim **33** wherein converting the desired intensity to a desired speed comprises using a combination of a model which maps locomotion intensity to locomotion speed and subject specific calibration data.

57. A method according to claim **56** wherein the subject specific calibration data is used to reduce an experimentally determined error between predictions of the model and measured calibration data.

58. A method according to claim **57** wherein the experimentally determined error comprises a combination of experimentally determined errors associated with the model at different intensity levels.

59. A method according to claim **33** wherein converting the desired intensity to a desired speed comprises using experimentally determined subject specific calibration data that maps locomotion intensity to locomotion speed for the subject and for a plurality of discrete intensity levels.

60. A system for automatically controlling a locomotion speed of a human or other animal subject, the system comprising:

one or more sensors for sensing one or more corresponding parameters of the locomotion movement of the subject and for generating therefrom a measured speed which represents an estimate of the subject's actual locomotion speed;

a controller configured to: determine an error comprising a difference between a desired speed and the measured speed and output, to the subject, a stimulus frequency signal;

wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a manner that matches a frequency of the stimulus frequency signal, the subject's actual speed controllably tracks the desired speed.

61. (canceled)

62. A system for automatically controlling a locomotion position of a human or other animal subject, the system comprising:

one or more sensors for sensing one or more corresponding parameters of the locomotion movement of the subject and for generating therefrom a measured position which represents an estimate of the subject's locomotion position;

a controller configured to: determine an error comprising a difference between a desired position and the measured position and output, to the subject, a stimulus frequency signal;

wherein the stimulus frequency signal is based on the error in such a manner that when the subject ambulates in a

manner that matches a frequency of the stimulus frequency signal, the subject's actual position controllably tracks the desired position.

63. (canceled)

64. A system for automatically controlling a locomotion intensity of a human or other animal subject, the system comprising:

one or more sensors for sensing one or more corresponding parameters of the locomotion movement of the subject and for generating therefrom a measured speed which represents an estimate of the subject's actual locomotion speed;

one or more sensors for sensing one or more corresponding parameters correlated with an intensity indicator of the subject and for generating therefrom a measured intensity which represents an estimate of the subject's actual locomotion intensity;

a controller configured to:

determine an intensity error comprising a difference between a desired intensity and the measured intensity; and

if the absolute value of the intensity error is outside of a threshold region around the desired intensity:

convert the desired intensity to a desired speed;

determine a speed error comprising a difference between the desired speed and the measured speed; and

output, to the subject, a speed-based stimulus frequency signal wherein the speed-based stimulus frequency signal is based on the speed error in such a manner that when the subject ambulates in a manner that matches a frequency of the speed-based stimulus frequency signal, the subject's actual intensity approximately controllably tracks the desired intensity; and

if the absolute value of the intensity error is within the threshold region around the desired intensity:

output, to the subject, an intensity-based stimulus frequency signal wherein the intensity-based stimulus frequency signal is based on the intensity error in such a manner that when the subject ambulates in a manner that matches a frequency of the intensity-based stimulus frequency signal, the subject's actual intensity controllably tracks the desired intensity.

65. (canceled)

66. A method according to claim **7** wherein the stimulus frequency signal is provided to the subject in a form of music and the control signal is updated at one or more intervals within a musical piece.

67. (canceled)

68. A method according to claim **35** wherein the speed-based stimulus frequency signal is provided to the subject in a form of music and the speed-based control signal is updated at one or more intervals within a musical piece.

69. A method according to claim **40** wherein the intensity-based stimulus frequency signal is provided to the subject in a form of music and the intensity-based control signal is updated at one or more intervals within a musical piece.

70.-71. (canceled)

* * * * *