CONTRIBUTION OF MUSCLE TO OPTIMAL PERFORMANCE IN SIMULATED OVERARM THROWING

by

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Contribution of muscle to optimal performance
in simulated overarm throwing.

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ABSTRACT

Multisegmental skills, such as throwing, kicking and striking with an implement are sometimes characterized by the common objective of projecting a missile a large distance. When performed successfully, these skills demonstrate similar patterns of motion. Kinematic studies have shown a proximal to distal sequencing of segmental motion, with the velocity of the most distal segment peaking higher and later than that of the more proximal segments. The observed pattern of motion has been accounted for by i) the nature of the segmental linkage, and ii) the mechanical properties of the muscles contributing to the motion. The first objective of this thesis was to determine the role of muscle in producing the observed behaviour of the system, including the influence of proximal antagonism late in the throw. The second objective was to determine the sensitivity of performance to changes in the mechanical properties of muscle. An understanding of the way in which muscles influence the manner in which linked segments interact is beneficial in terms of maximizing a desired output.

A computer model was used to simulate planar overarm throwing. The model comprised three linked segments and six single equivalent, Hill-based muscle models providing agonistic and antagonistic influence at each joint (shoulder, elbow and wrist). A forward dynamics approach was used to determine the kinematics of each throw from a set of initial conditions. The success of a throw was evaluated by the horizontal distance the ball was projected from its position in the hand at the time of release.

Throws which resulted in greater projectile distances were associated with a large increase in energy of the most distal segment prior to release of the ball. This increase in energy was achieved by optimal levels of work done by the shoulder and elbow agonists. The greatest percentage of total work was done by the shoulder agonist. In addition, there was a passive transfer of energy across the wrist joint by means of joint force power. Optimal timing and sequencing of onset of activation of all muscles was necessary to bring about maximal performance. Development of an antagonistic torque at the most proximal joint did not enhance throwing performance.

Modifications to the parameters defining the strength and speed of muscle resulted in improved throwing performance. In some instances, changes to the properties of muscle necessitated adaptation of the times of muscle onset in order to maximize performance. In general, changes to the properties of the shoulder agonist were more influential than changes at the elbow, which in turn were more influential than changes at the wrist. The improvement was accounted for by the increased impulse provided to the system. Changes to the elastic property of muscle had less influence on throwing performance. The largest effect was brought about by modifying the stiffness of the elbow extensor series elastic component. The implications of these results lie in the fact that all individuals exhibit different muscle properties and that the properties of muscle can be modified through physical training. As a result, the exact timing of activation of the muscles involved in executing skilled motion must take into account individual differences in order to maximize performance.

Dedication

To my family,
especially Mom and Dad
who never let me say
I can't.

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Not content with the ingenious and useful Application of Levers, Ropes and Pulleys; to the Bones, Muscles and Tendons, and other valuable mechanical and hydrostatical Pursuits : Not content with these, I say, Millstones were brought into the Stomach, Flint and Steel into the Blood-vessels, Hammer and Vice into the Lungs, &c. But all to no good Purpose; there being certain Bounds which mechanical Principles and Demonstrations do not reach.

Stevenson, 1771

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Chapter 1

INTRODUCTION

Humans can move their bodies in a skillful manner to achieve a desired goal. To do so, they must learn to activate muscles in such a way that appropriate forces are developed in a timely manner. The result is a smooth and orderly sequence of limb movement. This is exemplified in activities ranging from the common task of reaching to grasp an object to the complex sequence of movements involved in pitching a fastball. Success depends upon the ability to optimize the use of the physical characteristics of the body within the limitations imposed by the laws of mechanics.

While coordinated motion appears to be effortless for the accomplished athlete, identification of principles which underlie such coordination is difficult. The complexity of the problem can be attributed to the number of factors which play an integrated role in governing the behaviour of the musculoskeletal system. The neural, muscular and mechanical properties of the system must all be considered. The system must work within the limitations imposed by muscular strength, joint range of motion, gravity, and the characteristics of implements or environmental factors with which it may interact. In order to formulate principles of motor coordination, an integrated approach is necessary to address how contributions of all factors combine to produce the final outcome.

The general aim in this thesis is to investigate the mechanisms underlying optimal performance in multisegmental, ballistic skills. The skills which are of particular interest include throwing, kicking and striking with an implement. A common goal of these activities is to project an object with maximal velocity in a given direction. To attain the necessary high endpoint velocity and optimal orientation of the distal segment at release or impact, coordinated movement involving optimal timing and sequencing of the contributing segments is required. The coordinated pattern of motion which has proven successful involves an orderly recruitment of segments as demonstrated by segmental or joint angular velocities which peak in succession in a proximal to distal sequence.

Many skills of this nature have been studied resulting in a compilation of kinematic and kinetic profiles which are indicative of typical movement patterns for each activity. These analyses are often used to compare athletes of differing skill level with the purpose of improving the technique of less skilled athletes. While comparisons of kinematic data may provide some benefit to a novice individual in terms of understanding what the athlete is trying to achieve, little information is provided about how to achieve it. In order to understand how to maximize the desired output for each skill, it is necessary to incorporate kinetic information. Once the mechanisms underlying optimal performance are understood, a rationale for advocating a particular technique to athletes will exist. However, there are limitations to this approach because individual differences of the participants are generally not taken into consideration. Pooled data from a population of athletes cannot necessarily provide information that is specific to a particular athlete.

In this thesis, coordinated motion was investigated by examining the behaviour of the musculoskeletal system during an optimally executed movement, and by determining the influence of changes to the mechanical properties of muscle on the outcome of skilled motion. Utilization of the experimental method to achieve this objective has a number of limitations. Firstly, it is not possible to measure, for a given individual, all of the musculoskeletal characteristics which may influence performance. Similarly, it is not possible to exert rigorous control over changes to those characteristics. Secondly, the approach whereby many subjects are studied can be time consuming and finally, the results obtained are limited by the degree of accomplishment of the subject population used. Consequently, an alternative approach was taken in which the musculoskeletal characteristics were modelled, with neural input provided by activation profiles to each muscle model. An advantage of this method is that each characteristic of interest (muscular, skeletal, or neural) could be varied independently to determine its relative importance in affecting the behaviour of the system. In doing so, a general understanding of the mechanisms underlying optimal performance was obtained, and altering the muscle characteristics allowed the model to mimic different individuals doing the same task.

This thesis is divided into six chapters. Firstly, the behaviour of multisegmental systems during various ballistic activities is described, followed by explanations of the possible mechanisms which underlie the observed patterns of motion. In addition, a basis for contribution by the mechanical properties of muscle is provided. Secondly, the structure of the computer model used to simulate overarm throwing is described. The segmental and muscular properties are defined, and the process by which a simulated throw is produced is explained. The following three sections include the methods, results and discussion pertaining to each of the three primary objectives of this thesis. General conclusions and recommendations are stated in the final section.

OBJECTIVES

This thesis was concerned with optimal human movement. In order to maximize or minimize a performance criterion, there must be appropriate coordination and interaction of neural, muscular and skeletal structures. The task of simple, planar overarm throwing with the goal of projecting a mass as far as possible was chosen for study. A computer modelling and simulation approach was used in order that the physical characteristics of the system could be independently manipulated and the effect of such modifications could be determined. For a given set of segmental and muscular characteristics, the times of onset of activation of all muscles were optimized, resulting in maximal throwing performance.

The primary objective of this thesis was to determine the manner in which muscles contribute to optimal behaviour of the multisegmental linkage.

The second objective addressed the possibility that performance can be enhanced by actively inducing a transfer of momentum and/or energy from the proximal to the more distal segments by developing an antagonistic torque at the most proximal joint in the system.

The final objective was to determine the sensitivity of throwing performance to changes in the mechanical properties of the muscles involved in simulated throwing.

REVIEW OF LITERATURE

GENERAL MOVEMENT PATTERN OF MULTISEGMENT BALLISTIC SKILLS

In performing ballistic activities such as throwing, kicking and striking, the body is defined as an open, linked system of rigid segments. The most distal segment is constrained only by its connection at its proximal end to its proximal neighbour. The implication of this segmental arrangement is that in multisegmental motion, the movement of one segment affects that of other segments in the system. An understanding of the way in which the linked segments interact is beneficial in terms of maximizing a desired output.

Skills in which the objective is to maximize the projected range or velocity of an object demonstrate distinctive movement patterns whereby there is sequential involvement of segments beginning with the most proximal segment in the linkage. In the case of throwing, this was described by Atwater (1979) as "the sequential action of body segments progressing from the larger, slower-moving trunk actions to the faster, distal actions of the relatively smaller arm and hand segments". The summation of speed principle (Bunn, 1972) describes the proximal to distal sequencing of segmental motion in sporting skills. It states that the movement should start with the more proximal segments and progress to the more distal segments such that each segment starts its forward motion at the instant of greatest speed of the preceding segment and reaches a maximum speed greater than that of the more proximal segment.

The success of a proximal to distal sequencing of segmental motion is evident in many sporting skills and has been described using a variety of kinematic parameters. Whiting et al. (1991) found that longer javelin throws were typified by an orderly progression of hip-shoulder-elbow-javelin linear velocities compared to the shorter range throws which demonstrated temporally coincident occurrence of peak shoulder and elbow velocities. In a study of competitive female handball players, all subjects demonstrated a proximal to distal peaking of segmental endpoint linear velocities, but the main differences between the good and poor throwers were higher maximal velocities and greater deceleration of the proximal segments just prior to release (Joris et al., 1985). In punt kicking, Putnam (1983) reported that the peak angular velocity of the thigh preceded that of the shank such that highest foot speed occurred at ball contact. There is a similar succession of peak joint angular velocities in expert taekwondo axe kicking (Lee and Phillips, 1992). Striking skills such as volleyball serves (Luhtanen, 1988), tennis serves (Van Gheluwe and Hebbelinck, 1985), badminton smashes (Ye, 1991) and field hockey penalty hits (Elliot and Chivers, 1988) are all characterised by a sequential peaking in segmental angular or linear endpoint velocities with that of the most distal segment being highest at, or near, impact with the missile.

Skill Specific Differences

Although proximal to distal segmental motion is a robust characteristic of many multisegmental skills, there are skill specific differences in the kinematic profiles. One reason for these differences is variation in the objective of the skill. Subjects striking a ball with the objective of either speed or accuracy demonstrated different segmental movement patterns (Southard, 1989). In the condition of striking the ball to obtain maximal speed, there was a sequential peaking of upper arm, forearm and hand velocities; whereas, when accuracy was the objective, the upper arm and forearm were constrained by the subjects to act in a unitary manner. The control of ball velocity and accuracy are also important determinants of successful baseball pitching. The analysis of fastball and curveball pitches indicated that early in the action, variation in the two pitches is minimal in order that little useful information is provided to the batter (Elliot et al., 1986). However, prior to the point of ball release, there are differences in forearm and wrist motion which influence the resulting flight of the ball. A comparison of throwing for distance and throwing for speed indicated no significant difference in resultant velocity at release (Miyanishi et al., 1993). There were differences in release height, angle and the velocity components of the ball, hand and wrist which were attributed to differences in the motions of the upper arm and torso.

Throwing performance is also affected by the number of body segments which contribute to the execution of the skill (Toyoshima et al., 1974). When subjects used a normal throwing pattern with a foot step, the velocity of the ball was more than twice that during a throw in which the subject's upper arm was immobilized, allowing movement of only the forearm and hand. The consensus from research investigating body segment contributions in overarm throwing is that approximately half of the velocity at release is due to the initial step and trunk rotation.

The range of motion through which segments rotate in a particular skill is another factor which can account for different kinematic profiles. In a comparison of the overhand throw between males and females, Sakurai et al. (1991) attributed the greater throwing distances of the males to increased joint rotation in the direction opposite to that of the throw. This enhanced backswing movement led to increased range of motion about each joint. Comparison of a football punt and place kick indicated greater speeds of the foot in the punt because the useful ranges of hip flexion and knee extension were greater (Roberts and Metcalfe, 1968). Three similar activities in which the lower limb segments rotate through different ranges of motion are the swing phase during kicking, running and walking. Although each activity demonstrated a proximal to distal sequencing of thigh and leg angular velocities, the results indicated differences in the relative magnitudes of segmental velocities and in the timing of specific events (Putnam, 1991).

Differences in the characteristics of the projected object also result in modifications to the technique employed. Wilson et al. (1989) reported changes in the relative timing of peak segment angular velocities during maximal velocity planar arm movements when different masses were held in the hand. However, the general principle of proximal to distal sequential timing was evident in all conditions.

Finally, individual differences in the physical characteristics of the athletes also account for the variations observed in the performance of each skill. Pedegana et al. (1982) showed a relationship between the strength of the elbow extensors and wrist extensors and throwing speed in professional baseball players. However, no explanation was provided for this relationship due to the complexity and interactive nature of the factors which lead to maximal throwing velocity. Skilled volleyball players of different ages were filmed while performing the overarm serve (Luhtanen, 1988). The eldest group demonstrated proximal to distal temporal profiles of the segment angular velocities and greater magnitudes of the velocities. The younger players who produced lower ball velocities did not always show this sequence. The advantage was accounted for by the greater segmental lengths and masses of the older subjects which caused a greater ball velocity after impact.

The importance of assessing technique on an individual basis was emphasized by Whiting et al. (1991). A number of parameters (release speed, last-step length, knee flexion and temporal profiles of joint angular velocity) were used to differentiate between long and short javelin throws by eight subjects. Some participants produced short throws and long throws but the explanation provided for the success (or lack of success) of each individual varied. Even though greater range throws were generally associated with greater release speeds, one subject showed no difference in release speed between a long and short range throw. One variable which was used to account for the difference in their performance was a greater release angle, a feature not seen in other individuals. However, this approach whereby individual differences were assessed did not include consideration of physical differences.

MECHANISMS CONTRIBUTING TO THE OBSERVED MOVEMENT PATTERN

The summation of speed principle (Bunn, 1972) suggests that the speed of the distal end of the link-segment system increases by summing the individual speeds of all of the contributing segments, but the principle does not explain how this is achieved. The difficulty in providing a mechanical explanation is that in multisegmental linkages, the motion of one segment within the system cannot be attributed solely to the muscle forces acting on that segment (Putnam, 1991). "Each segment in a linked system influences the motions of its adjacent segments in a way that is dependent on how the segment is moving and on how the segment is oriented relative to its adjacent segments", (Putnam, 1993). Because the motion of a segment is the result of the application of muscular and joint forces acting on it, these forces must be applied in a controlled and systematic fashion in order for the segments to move in the coordinated manner required of optimal performance. It is the role played by muscles on coordinated multisegmental motion that is of interest in this thesis; however, it can not be studied without recourse to the dynamic segmental interaction.

The two primary properties which must be considered in establishing the mechanical basis underlying sequential movement are the nature of the segmental linkage and the mechanical characteristics of the muscles. The complexity of the problem arises from the nonlinear nature of these contributing factors. The nonlinearity of musculotendon dynamics and intersegmental dynamics requires modelling and simulation to understand fully the significance of the interaction between the various components of the system (Zajac and Winters, 1990). However, there have been attempts to address the contributions of both of these factors through empirical studies.

Transfer of momentum is a frequently cited explanation for the observed proximal to distal sequencing of peak segmental velocities. When the larger, more proximal segments are moved forward then stopped, the momentum developed is transferred to the smaller, more distal segments. The increase in velocity of the more distal segment is greater than the decrease in the proximal one because of the relative difference in mass between the two segments. Visual and kinematic assessments of high speed sporting skills have led to the assumption that the observed deceleration of proximal segments is due to antagonistic muscle moments at the proximal joint (Alexander, 1983; Ye, 1991; Plagenhoef, 1971). An alternative means of initiating the transfer of momentum was suggested by Whiting et al. (1991). In javelin throwing, the higher velocities in the distal segments were attributed to the final plant of the front leg which was said to break the thrower's forward momentum and act as a link in the system of transferring momentum up through the body to the throwing arm. The means by which energy was transferred between segments was not addressed.

Although it is attractive to assume a causal relationship between proximal segment motion and the observed increases in distal segment velocity, mechanical evidence is required to support the suggested theories. This rationale was the basis for several investigations which have quantified segmental interactions with the goal of determining how the action of one segment influences that of adjacent segments.

Feltner and Dapena (1986) analyzed in three dimensions net joint forces and torques during maximal velocity baseball pitches to understand better the causal factors responsible for producing the observed motion. The findings indicated that the shoulder and elbow muscles were not directly responsible for producing all segmental motions during the pitch. For example, during the initial phase, the upper arm experienced extreme external rotation against the action of an internal rotation torque at the shoulder joint. The external rotation was produced by a combination of trunk rotation and the inertial lag of the forearm and hand as the more proximal segments rotated forward.

The rapid elbow extension which occurred prior to release was not due to the activity of the triceps (Feltner, 1989). Elbow extension velocities in the range of 38 radians per second were attained with low magnitudes of elbow extension moments (peak value of 20 Nm). The resultant joint force exerted by the upper arm on the forearm at the elbow accounted for the observed elbow extension. This is supported by Dobbins (reported in Roberts, 1971) who recorded surface EMG of the triceps and biceps simultaneously with elbow angle during overarm throwing. One subject received a radial nerve block which paralyzed the activity of the triceps and wrist and finger extensors. With the anesthetic, ball velocity dropped from 80 feet/second to 35 feet/second; however, on subsequent throws, the subject adjusted his performance and was able to increase ball speed to 65 feet/second. The moderate levels of triceps activity during elbow extension in the control throw support Feltner (1989) who suggested that elbow extension was produced mainly by the actions of the proximal segments.

The pattern of motion for kicking is similar to that of throwing in that the angular velocity of the shank peaks higher and later than that of the thigh. Robertson and Mosher (1985) attributed the decrease in thigh angular velocity to the hip extensor torque observed late in the swing phase, but did not provide a rationale for the subsequent increase in knee extension velocity which occurred in the absence of a knee extensor torque. Contrary to this finding, Putnam (1983) found that the decrease in the angular velocity of the thigh occurred as a result of the influence of the shank's angular motion on the thigh, and not to a hip extensor torque.

Putnam (1983, 1991, 1993) used a segment interaction analysis to validate the principles which have been proposed to account for the contribution of the proximal to distal segment motions to the actions of kicking and the swing phase of running and walking. In these analyses, all segmental motion was expressed in terms of the joint moments and motion-dependent moments. The motion-dependent moments are functions of angular motion variables, and were used to explain the influence of the thigh's angular motion on the leg, and the influence of the leg's angular motion on the thigh. It was concluded that the proximal to distal sequential motion of the swinging leg occurs to a large extent simply because of the mechanical behaviour of linked systems.

The viewpoint that segmental linkages move the way they do for purely mechanical reasons is also maintained outside of sporting literature. For example, when addressing the problem of how we control our arms, Greene (1982) suggested that rather than placing many demands on the nervous system to achieve a desired trajectory of the hand, whenever possible, we should let the arm swing under its own momentum and allow the laws of mechanics to move it for free. This theory is supported by Goodman (1985) for goal directed arm movements. Kelso and Saltzman (1982) also emphasized the importance of exploring the contributions of the dynamics of the system before trying to explain control strategies used by the nervous system.

Even though we are cognizant of the importance of the mechanics and mechanical principles in governing multisegmental motion, the contributions of the muscle actuators must not be neglected. For any human movement, "the final output of the nervous system can directly affect only the activity of the muscles. The muscular activity, in turn, establishes relationships among the mechanical variables about joints (torque, angle, and their derivatives) without specifying the value of any single variable", (Hasan et al., 1985b, p183). The interaction of the nervous system and the segmental linkage has been studied during locomotion and the possibility exists that the "motor output is 'tuned' to the utilization of mechanical interactions among joints", (Hasan et al., 1985b, p182). Not only must the nervous system take into account the dynamics of the mechanical system, but it must also use strategies that account for the dynamic properties of muscle, (Partridge, 1979). It is possible that the nervous system may be able to take advantage of certain properties of muscle to accomplish the desired result with greater ease.

The coordinated movement patterns seen in sporting skills are governed, at least in part, by the intrinsic properties of muscle. Typically, throwing, kicking and striking skills are executed in two phases. The first is the use of a backswing or wind-up prior to executing the second phase, which is the motion in the forward direction. During the backswing, the agonistic muscle is stretched by either antagonistic activity or gravity, then it is forced initially to contract eccentrically to reverse the backswing and bring about movement in the desired direction. Also, once the forward phase of the movement has been initiated, the proximal to distal sequencing of segment rotation allows the more distal muscles to act in the same manner because the forward rotation of a proximal segment causes the adjacent distal segment to lag due to its inertia. This series of motions has a positive influence on the muscle force produced during the concentric phase of the movement. The combination of eccentric and concentric contractions described is a functional system called the stretch-shortening cycle (Komi, 1984).

In throwing, Joris et al. (1985) stated that the prestretch in the muscles responsible for shoulder rotation and wrist flexion enabled these muscles to do more work than if they were to have developed force from rest. This physiological phenomenon was forwarded as one explanation for the observed proximal to distal sequencing of segmental actions. A similar movement pattern exists in kicking. The knee extensor torque develops while the knee joint is flexing which enables this muscle group to take advantage of the stretch-shortening cycle. However, in both of these skills, the forward acceleration of the distal segment is only accounted for in part by muscular contributions. The segmental interactions, rather than elbow extensor moments are said to be the primary cause of elbow extension in throwing (Feltner, 1989) and in kicking, the knee extensor moment and the interactive moment are approximately of equal magnitude (Putnam, 1993).

SIMULATION OF MULTISEGMENTAL MOTION

Biomechanical modelling of the human musculoskeletal system is evolving as a means of studying how and why the body coordinates muscles during multijoint movement. This approach is motivated by increased interest in improving performance, reducing injury and improving training (King and Huston, 1989). The existing models range in complexity and address a variety of problems.

Computer modelling and simulation have been used to quantify and understand the influence of proximal segment motion upon the distal segment during rapid swing motion of the lower limb (Phillips et al., 1983). Non-muscular intersegmental reactions were studied in a two segment linkage by considering intersegmental muscular forces and moments to be zero. Late in the swing, when the speed of forward rotation of the thigh was decreased by the application of a hip extensor torque, knee extension occurred without a knee extensor moment. If, however, the hip extensor torque was applied too early then knee flexion, rather than extension occurred. These simulated experiments indicate that non-muscular intersegmental reactions can play a substantial role in influencing the distal segment in swing motions. In order for the desired results to occur, there must be favourable positioning of the segments and appropriate timing of the onset of muscle torques.

A three-link segment model of planar overarm throwing was developed to determine if muscular or segmental properties of the system play the greatest role in determining why proximal to distal sequencing of motion is best (Herring and Chapman, 1988). The physiological properties of muscle were removed from the system, and the influence of muscle was achieved with fixed, arbitrary torques as input at each joint. Maximal ball range occurred with a proximal to distal onset of torque generators and a proximal to distal sequencing of resultant velocities of the elbow, wrist and ball. Because the joint torque actuators were independent of mechanical properties of muscle, the findings suggest that the coordinated pattern of motion can be accounted for largely by the mechanical properties of the limb segments and the way in which they are linked. When the segmental characteristics (mass and length) were modified over a physiological range (+/- 10%), the timing of joint torque onsets was affected, but optimal performance still resulted from a proximal to distal sequencing of torque onset.

The effect of timing of muscle onset on maximizing ball velocity in throwing was studied using two-segment linked models with one muscle at each joint (Alexander, 1991). The torque produced by the muscle models was a function of angular velocity, but independent of joint angle. In each simulated throw, each muscle was either inactive or fully active at any given time. The optimal time delay between the onset of the two muscles resulted in the total work done by the two muscles to be greater than if the delay was too short or too long. The increased work done allowed more energy to be imparted to the ball. Faster throws were made possible by making the muscles either stronger or faster. The results from this model supported the role of transfer of energy and momentum in determining the optimum sequence of muscle action.

MODELLING AND SIMULATION APPROACH

The preceding discussion on the contributions of both intersegmental interactions and the mechanical properties of muscle to the observed movement pattern in multisegmental skills indicates the importance of being able to study each in detail, and to determine the implication of modifications to each on the resulting pattern of motion. Computer modelling and simulation are necessary to achieve these objectives.

One of the primary concerns in modelling is achieving the appropriate degree of complexity. If the model is too simple, fundamental features may not be included and the model is inadequate. Overly complex models make interpretation of the results difficult. "Mathematical models must efficiently capture the essence of the phenomenon of interest. They should contain those output variables central to the inquiry and, through the appropriate physical principles, the relationships which exist between the outputs and the most important input or decision variables which are of interest to the designer, coach or athlete", (Hubbard, 1993, p53).

There are two philosophies concerning the selection of model complexity. The first is to begin with a simple model which is an approximation, and includes only those variables which are considered to be most influential while neglecting variables which are judged or calculated to be of minor importance. Subsequent models evolve through the successive addition of the next most significant element (Hubbard, 1993). The alternative philosophy is one in which a complex model is developed, followed by a systematic investigation of the sensitivity of behaviour to changes in model parameters. Those parameters which indicate low sensitivity can be eliminated from future models, (Zajac and Winters, 1990). The model used in this thesis was simple, yet was considered sufficient to meet the objectives of the thesis.

One common goal of research using musculoskeletal models is to understand how intermuscular control, inertial interactions among body segments and musculotendon dynamics coordinate multisegmental motion (Pandy, 1990). To this end, musculoskeletal models have been used to study the supposed unique role of bi-articular muscles in powerful leg extensions in vertical jumping (Ingen Schenau et al., 1990; Pandy, 1990). The specific influence of musculotendon properties on performance and coordination during jumping was investigated by Pandy (1990) by modifying the parameters defining the mechanical properties of muscle. The predictive value of dynamic simulations was emphasized by Yamaguchi (1990) in the context of gait analysis. For example, the effects of surgery, physical therapy and orthotic intervention could potentially be predicted before the actual alterations are performed.

In this thesis a model was used to gain insight into the contribution of muscle properties to the dynamics of a multisegmental system during throwing. The emphasis underlying the development of the model was to represent the general behaviour of muscle. An attempt was made to include relevant physiological properties but a number of simplifications were made. For example, the influence of all muscles crossing a given joint was represented by one agonistic and one antagonistic single equivalent muscle on each side of the joint. Secondly, no distinction was made between contributions by uniarticular and multiarticular muscles. However, one advantage of the chosen design was that it allowed modifications to be made to each characteristic of the model so that the sensitivity of performance to each muscle property could be determined.

The nature of the segmental linkage used in the model was also a simplification of human structure. The throwing motion was constrained to act in a single plane allowing motion in only two-dimensions. In addition, contributions from the legs and trunk were excluded from the model. However, it is proposed that the characteristics of the model are sufficient to provide insight into the underlying principles which govern human performance.

MUSCLE FORCE REGULATION

The link-segmental nature of swinging limbs has been shown to predispose the system to proximal to distal sequencing (Herring, 1989). The contribution of the mechanical properties of muscle has been addressed to a lesser extent. In order to elucidate how the properties of muscle are implicated in the proximal to distal segmental motion, the means by which force is developed in muscle must be understood.

The force that a muscle is able to produce is a function of neural activation, the current state of the muscle (length and velocity) and events which precede the contraction.

As a result, there is a limit to what the muscle is able to accomplish in a given situation, depending upon the conditions of the muscle contraction. On the other hand, there are also conditions in which a muscle is able to enhance its force producing capabilities. Therefore, it would be advantageous for an athlete to make use of this property of muscle when trying to maximize force production while executing a multisegmental skill.

The mechanical properties of muscle have been described mathematically and incorporated into a model (Baildon and Chapman, 1983). The details of the muscle model are explained in the Methods (Chapter 2), but the properties which comprise the model are described here.

Activation

Force development in muscle occurs under the control of the central nervous system. The activation of a motor unit leads to force production in the muscle fibres which are innervated by the unit's motoneuron. A single action potential results in a rise and decline of isometric force, called a twitch. Larger forces are developed in whole muscle by activating many motor units. The magnitude of the total force developed in a muscle is a function of the firing rate and number of motor units which have been recruited.

Length

The cross-bridge theory of Huxley (1957) has been used to explain the isometric force-length relationship of muscle. When a muscle undergoes constant stimulation isometrically, it produces an active force that is defined as maximal at length Lo, and decreases at shorter and longer lengths. The force produced is accounted for by the amount of overlap of actin and myosin filaments, such that maximal force is produced with the maximal number of cross-bridge formations. When sub-maximal levels of activation are used, the general relationship between force and length is similar, but at any given length, the force is lower.

There is also a passive relationship between length and force in muscle. When muscle fibres are stretched, the parallel elastic component, found in connective tissue, begins to contribute significant force. Therefore, the total force in a muscle is the sum of the contributions from the active and passive components.

Velocity

When muscles undergo dynamic contractions, the force produced is a function of the velocity of the contraction. In shortening contractions, force is inversely proportional to velocity. At zero velocity, maximal isometric force is developed, and maximum shortening velocity occurs when the muscle is unloaded. Lengthening contractions occur when the load applied to a muscle is sufficiently large to overcome the isometric force of a muscle. In this situation, the muscle force is greater than that which is produced isometrically.

The level of activation influences the force-velocity relationship in the same manner that it influences the force-length relationship because the force-velocity relationship itself is a function of the isometric force-length relationship. There are differing theories regarding the relationship between the maximum velocity of shortening and activation. There is suggestion that maximal shortening velocity decreases with decreasing activation (Petrofsky and Phillips, 1981).

Stretch-Shortening Cycle

The force produced by a muscle in any contraction is also largely history-dependent. For simplicity, these history-dependent factors will not be considered in the current thesis. However, there is one situation in which the events preceding a concentric contraction are imperative to consider in light of the movement sequence used in throwing, kicking and striking skills. When a muscle contracts concentrically after having undergone an active lengthening, the force produced by the muscle is greater than that produced by a muscle which contracts concentrically from rest (Komi, 1984; Chapman, 1985). The benefits of this stretch-shortening cycle of muscle contraction are short-lived therefore there must be no delay between the stretch and shortening phases of contraction.

INFLUENCE OF PHYSICAL TRAINING ON MUSCLE PROPERTIES

The importance of identifying the relative contribution of the muscle properties to the successful execution of sporting skills lies in the fact that all individuals are different. Recognizing which characteristics of muscle are important for a particular skill may help to match individuals with those activities to which they are best suited. In addition, examination of the relative importance of the mechanical properties of muscle will reveal where training emphasis should be placed.

Physical training is used by athletes to try to augment performance; therefore, it is important that they use suitable training techniques in order to get the maximal benefit for improving their ability in a particular activity. The effects of different types of training regimens have shown that the resultant changes in muscle function are specific to the conditions of training. Therefore, in relation to sport performance, the training exercises should simulate the sport movement as closely as possible in terms of anatomical movement pattern, velocity, contraction type and contraction force (Sale, 1987).

Because throwing, kicking and striking require dynamic force production, rather than a pure increase in maximal strength, improvements in dynamic strength are necessary. Changes in the force-velocity relationship of muscle occur with dynamic training (Duchateau and Hainaut, 1984). There was an increase in maximal velocity of shortening of the adductor pollicis muscle after dynamic training, but there was no significant modification after isometric training. Not only must the distinction be made between isometric and dynamic methods of training, but in dynamic strength training, there is also a specificity of velocity. Training at low velocity increases low velocity strength but high velocity strength is unaffected. Similarly, training at high velocity improved high velocity strength more than low velocity strength (Sale and MacDougall, 1981).

Muscular power is increased by enhancing the force-velocity relationship of muscle. The objective in training is to identify the velocity which will maximize muscular power in dynamic contractions. In a study comparing the effect of training velocity on power production, subjects who trained at slow (1.05 rad/s) and intermediate (3.14 rad/s) velocities showed significant increases in power at all test speeds; whereas, the group who trained at a fast (5.24 rad/s) velocity, showed increased power only at faster test speeds (Kanehisa and Miyashita, 1983). Similar findings were reported by Coyle et al. (1981). There was a specificity of improvement of muscular power to the velocity of training, with an all-round effect being produced with an intermediate speed (180 deg/s). The specific influence of training with different loads on resultant power output in the elbow flexors was shown by Kaneko et al. (1983). Training with a load of 30% of maximal isometric force was most effective for improving maximal power, compared to the other conditions (0, 60 and 100% of maximal isometric force).

Further specificity of training was investigated through the implementation of power training using explosive type strength training (Hakkinen et al., 1985) and stretch-shortening cycle exercises (Kyrolainen et al., 1989). In these studies, the training consisted of several types of jumping exercises (squat jumps, counter-movement jumps and drop jumps, under different loading conditions). Prolonged power training of this nature resulted in specific training induced changes in neuromuscular performance. This was demonstrated by the greater improvements in the high velocity portion of the force-velocity relationship in comparison to the slight change in maximal strength (Hakkinen et al., 1985), and greater take-off velocities during the stretch-shortening exercises (Kyrolainen et al., 1989).

The mechanisms within the neuromuscular system which account for the specificity of the velocity effect during training are not well documented. There is some agreement that improvements in performance are due to neural factors rather than to changes in muscle contraction properties (Sale and MacDougall, 1981; Kaneko et al., 1983; Hakkinen et al., 1985). Possible neurological changes include the ability to recruit more motor units during the activity experienced in training (Coyle et al., 1981; Hakkinen et al., 1985; Kaneko et al., 1983) and a more economical usage of the motor units recruited so that a given number of motor units are more efficiently summated, resulting in a higher force output following training (Komi et al., 1978). The suggestion of preferential recruitment of slow twitch motor units during maximal slow velocity contractions has been refuted. In maximal voluntary contractions, there was similar activation of slow and fast motor units regardless of the velocity of the contraction (Desmedt and Godaux, 1979; Maton, 1980). In an investigation of training for fast force production, Hakkinen et al. (1985) concluded that improvements in performance can be accounted for by considerable neural and selective muscular adaptations, but that genetic factors may determine the ultimate potential for trainability.

In order to evaluate the relative contribution of training to induce changes in the properties of muscle, and training to improve technique in a particular skill on the performance of a rapid, unloaded movement (a karate punch), Voigt and Klausen (1990) investigated the influence of three different training programs. The first group consisted of karate students who participated in dynamic heavy progressive resistance exercise plus punch bag training. The second group of karate students participated in punch bag training only. The third group had no karate experience and underwent the same dynamic training regimen as the first group, but did not do any punch bag training. There was no significant correlation between the speed of the unloaded punch and maximal muscle strength. The ability to reach high angular velocities of the elbow joint during an unloaded punch was attributed to the ability to coordinate the movements of the body segments relative to each other during the execution of a punch. The conclusion was that the heavy resistive exercise enhances the gain in punching speed only when it is combined with specific punch training.

Changes in the elastic characteristics of muscle have been studied less than the active component of muscle. However, it was reported that the compliance of the series elastic component of the elbow flexors decreased after eccentric training (Pousson et al., 1990). The implication of this for stretch-shortening movements is that performance may be enhanced because a less compliant series elastic component may be able to transmit force more effectively.

One objective in this thesis is to identify the sensitivity of throwing performance to changes in muscle properties; therefore, it is necessary to know whether or not the simulated changes imposed on the model can actually be brought about physiologically. The observed changes in the force producing capabilities of muscle reported in the training literature indicate that increase in strength can manifest itself during both isometric and dynamic contractions. Once those properties of muscle which have the greatest influence on throwing performance are identified, training regimens can be planned to develop strength appropriately. This systematic approach reduces the possibility that athletes are trained inappropriately due to erroneous information gleaned from qualitative analyses.

Chapter 2.

METHODS

I. THE COMPUTER MODEL

A. Mechanical Characteristics of the Model

The model used to simulate overarm throwing comprised three rigid segments linked by pin joints. The three segments, representing the upper arm, forearm and hand are shown in Figure M1. The proximal end of the upper arm segment was fixed at the shoulder joint and motion of all segments was constrained to the sagittal plane. The system had a total of three degrees of freedom (flexion/extension at each joint). The segmental mass, length, position of the centre of mass (CM), and moment of inertia were characteristic of a male of mass 82.0 kg (Winter, 1979). The values of these parameters are given in Table M1. A ball of mass 0.18 kg was added to the hand segment at its centre of mass.

Table M1. Anthropometric parameters used in the model.

SEGMENT	MASS (kg)	LENGTH (m)	DISTANCE TO CM (FROM PROX END) (m)	MOMENT OF INERTIA ABOUT CM ($kg.m^2$)
UPPER ARM	2.296	0.3500	0.15260	0.029162
FOREARM	1.312	0.2975	0.12790	0.010662
HAND + BALL	0.672	0.1700	0.09335	0.001501

The relative joint angles of the model in the initial position are shown in Figure M1. The shoulder angle was defined relative to the vertical axis. However, the trunk

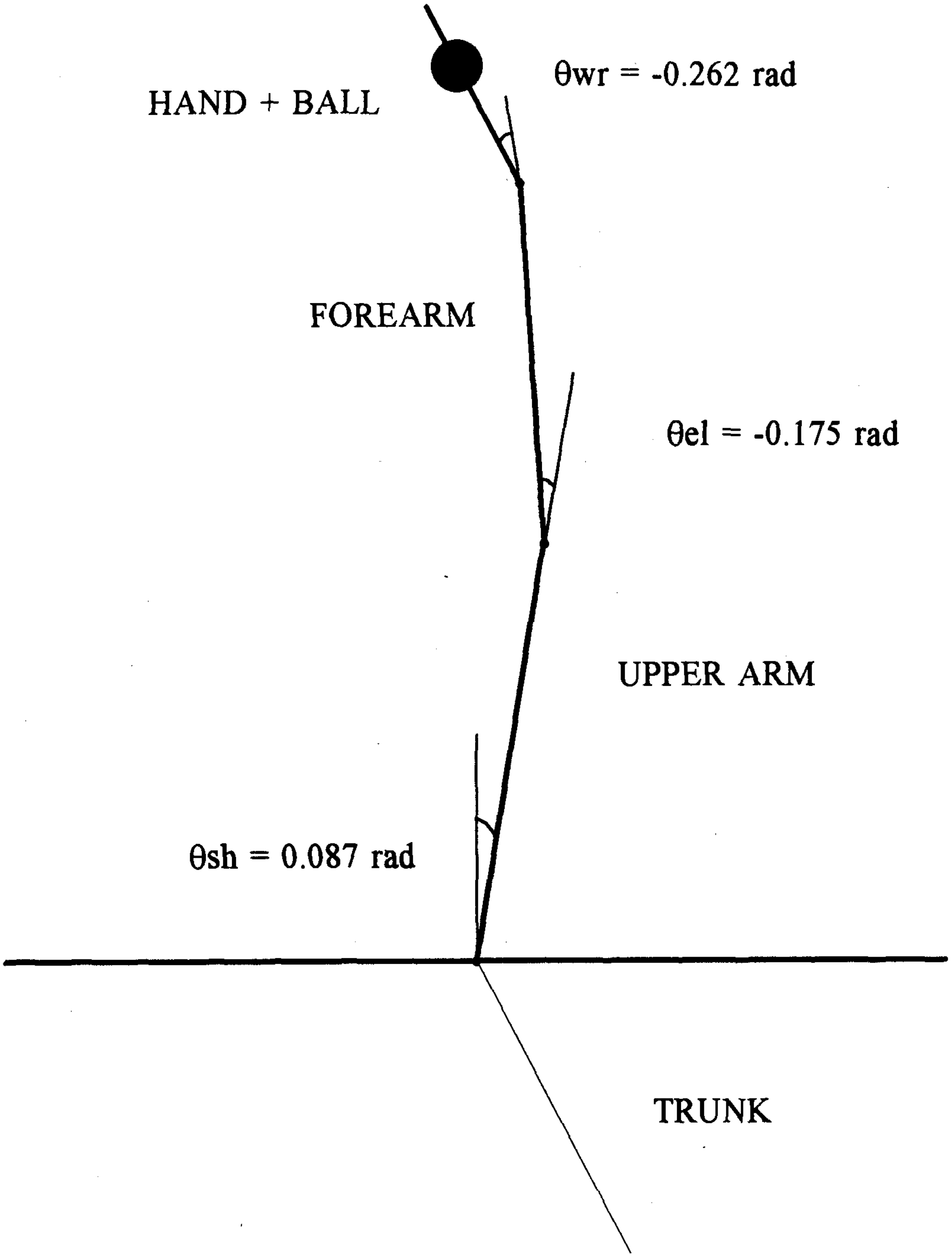


Figure M1. The computer model, shown in the initial position for a throw to the right. The segmental characteristics are given in Table M1.

segment was implicitly defined as being rotated backward an angle of 0.4 rad to the vertical. This allowed a greater range of motion for the muscles about the shoulder joint.

B. Muscular Characteristics of the Model

Muscular influence was provided to the model through the action of six single equivalent, uniarticlar muscle models. Agonistic torque production was provided by a shoulder extensor, elbow extensor and wrist flexor. Antagonism was brought about by a shoulder flexor, an elbow flexor and by a wrist extensor. A phenomonological modelling approach was used whereby the torque generating capabilities of the muscles crossing the shoulder, elbow and wrist were produced by a Hill-based model.

Each muscle actuator was modelled with the three component model depicted in Figure M2. Although muscle contractions result in the production of a force, muscles act about joints and therefore generate torques. These torques are dependent upon joint angle because the magnitude of the moment arm between the axis of rotation and the muscle changes with different joint angles. In order to simplify the model, a rotational model was used whereby muscular torques, rather than linear forces were generated. The relationships defining the torque producing capability of each component were modified from Winters (1985) and Winters and Stark (1988). The contractile component (CC) develops torque as a function of angle, angular velocity and activation. The series elastic component (SEC) is described by a non-linear elastic relationship, whose stiffness increases with activation. The parallel elastic component (PEC) is described by a passive stiffness which is significant primarily at the extremes of joint range of motion. In this configuration, the series elastic component transmits the torque generated by the contractile component to the two segments to which the muscle is attached. The torque

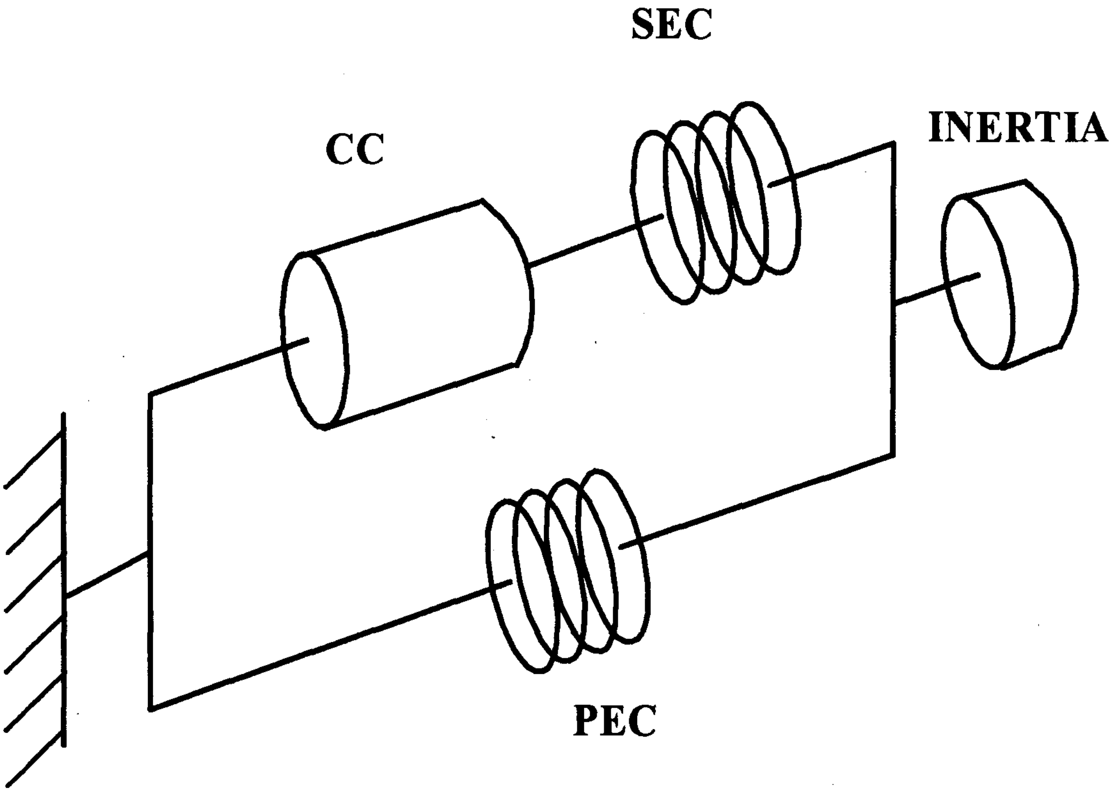


Figure M2. Three component muscle model comprising a contractile component (CC), a series elastic component (SEC) and a parallel elastic component (PEC)..

developed in the parallel elastic component is additive with that produced by the contractile component. The six muscles are modelled with the same structure, but the magnitudes of the parameters used to define each relationship were altered to represent appropriately the characteristics of each muscle. This was one of the advantages forwarded by Winters (1985) regarding the model structure. Once established, the model parameters are set and independent of the particular task. The equations defining each relationship are given in the following section. The values for each parameter are presented in Table M2 at the end of the following section, and the sources used to establish the parameter values are found in Appendix A. Once all of the relationships describing the elements of the model are described, the manner in which they were incorporated into the structure of the model is explained.

C. Relationships Describing the Mechanical Properties of Muscle

1. Contractile Component

a) Torque-Angle Relationship

The contractile component represents the active torque producing capabilities of a muscle. In a human joint, the overall active torque-angle relation is a function of the length-tension relationship of all muscles contributing to the movement and the instantaneous moment arm of each muscle which varies with joint angle. Winters (1985) used a gaussian-type fit and a linear function of the joint angle to characterize the torque-angle curves of a single equivalent muscle crossing a joint. The normalized maximal isometric torque produced by a muscle at a given angle and level of activation is defined by the following equation.

$$Mcc = \left(e^{-\left(\frac{\Theta cc - MXOO}{MXSH}\right)^2} + MXSL \times (\Theta cc - MXOO) \right) \times ACT \qquad (1)$$

where

Mcc: normalized moment produced by the contractile component
Θcc: CC angle
MXOO: angle at which maximal moment is produced
MXSH: constant - gaussian-type shape function
MXSL: constant - linear slope coefficient
ACT: activation level (on the interval <0,1>)

In Figure M3a, the torque-angle relationship for the elbow extensor is shown at four levels of activation. The magnitude of the torque in Figure M3a is expressed in terms of the actual torque-producing capability of the muscle rather than the normalized value, Mcc. This was achieved simply by multiplying each Mcc by MMAX, the maximal isometric torque. A compilation of the torque-angle relationships for the six muscles is illustrated in Figure M3b. The values of the parameters used to generate these relationships are given in Table M2.

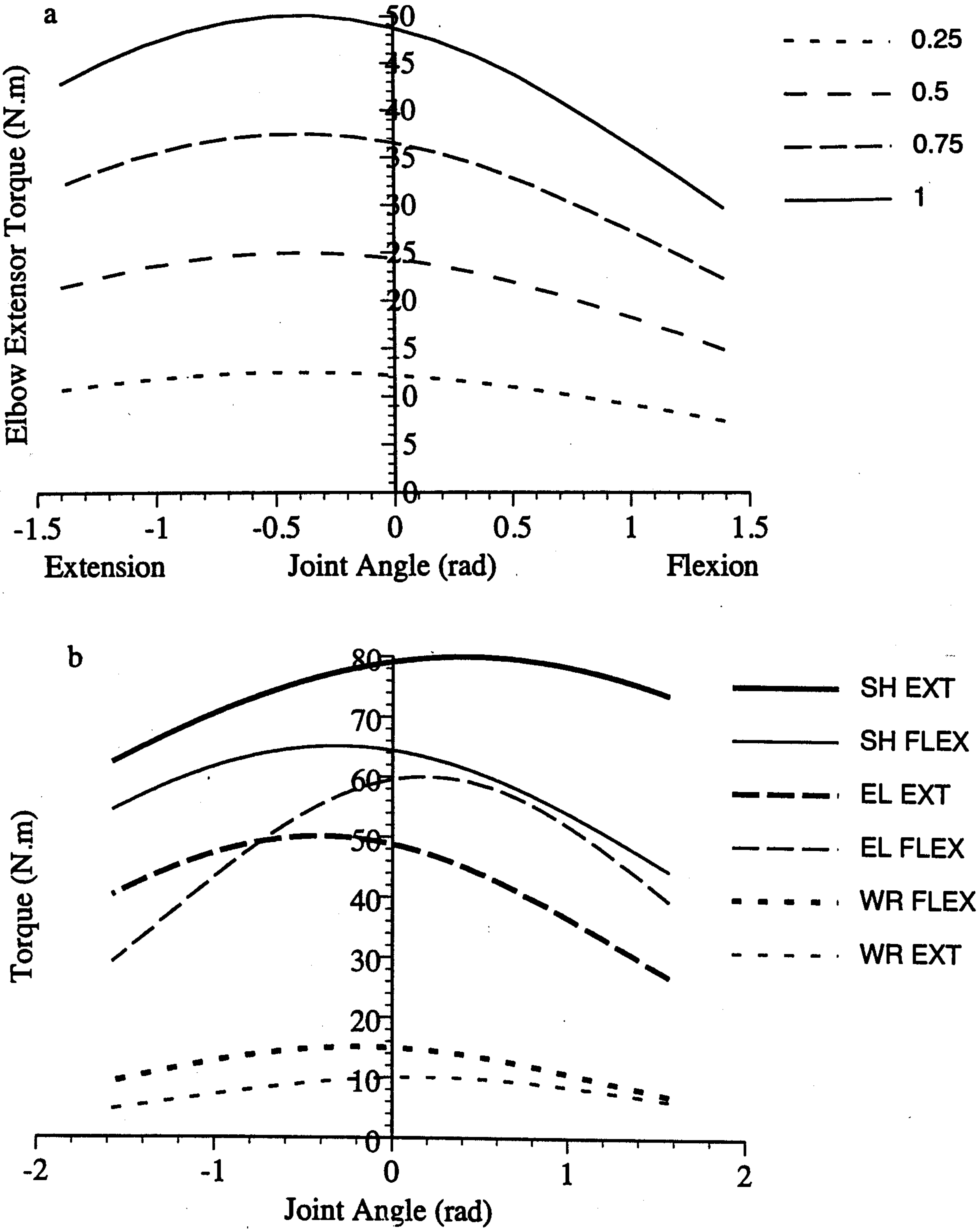


Figure M3. Torque-angle relationship for (a) the elbow extensor muscle at four levels of activation and (b) for all six muscles at maximal activation. The joint angular conventions correspond to those illustrated in Figure M8.

b) Torque-Angular Velocity Relationship

This relationship was originally defined by Hill (1938) and has been reformulated by Winters (1985) to describe the contractile process for both shortening and lengthening muscle. In lengthening contractions (angular velocity < 0), a muscle produces greater force than it does isometrically (angular velocity = 0), which in turn, is greater than the force produced in shortening contractions (angular velocity > 0). During lengthening contractions, if the maximal velocity of shortening is attained or exceeded, then the torque is calculated to be zero. At levels of activation below maximal, the maximal velocity of shortening is reduced, and at very low levels of activation it approaches a minimum of 50% of the original maximum. Generally, this relationship is defined so that a force or moment is calculated as a function of velocity; however, in this thesis Winters' (1985) equation was re-written so that torque is expressed in terms of angular velocity, as required by the muscle model algorithm.

Shortening:

$$\dot{\Theta}cc = \frac{BH}{\left(\frac{(1+MVSH)\times MH}{(MH-M)}\right)-1} \tag{2}$$

where

$$MH = Mcc \times MMAX$$
$$BH = MVSH \times VM$$

where

$$VM = \left(1 - MVER \times \left(1 - \frac{MH}{MMAX}\right)\right) \times MVVM \tag{3}$$

where

$\dot{\Theta}cc$: velocity of shortening of the contractile component
MVSH: shape constant defining the curvature of the hyperbola
MH: isometric torque capability at the given angle and level of activation
Mcc: normalized moment produced by the contractile component
M: current torque produced by the muscle
MVVM: maximal velocity of shortening of the muscle
MVER: constant - fraction of MVVM whereby VM at minimal activation will be a percentage (i.e. MVER) of MVVM at maximal activation
VM: maximal velocity of shortening capability of the muscle at the current angle and level of activation

Lengthening:

$$\dot{\Theta}cc = \frac{-BHL}{\left(\frac{((1+MVSH \times VMSHL) \times MH) \times (MVML-1)}{M-MH}\right)-1} \qquad (4)$$

where

$$VML = VM \times MVSHL$$
$$BHL = MVSH \times VML$$

where

MVSHL: shape constant for lengthening muscle
MVML: constant for maximal velocity of lengthening

The torque-angular velocity relationship for the elbow extensor, as a function of activation, is portrayed in Figure M4a. This relationship for each of the six muscles used in the model is given in Figure M4b. The values of the parameters used to generate these relationships are given in Table M2.

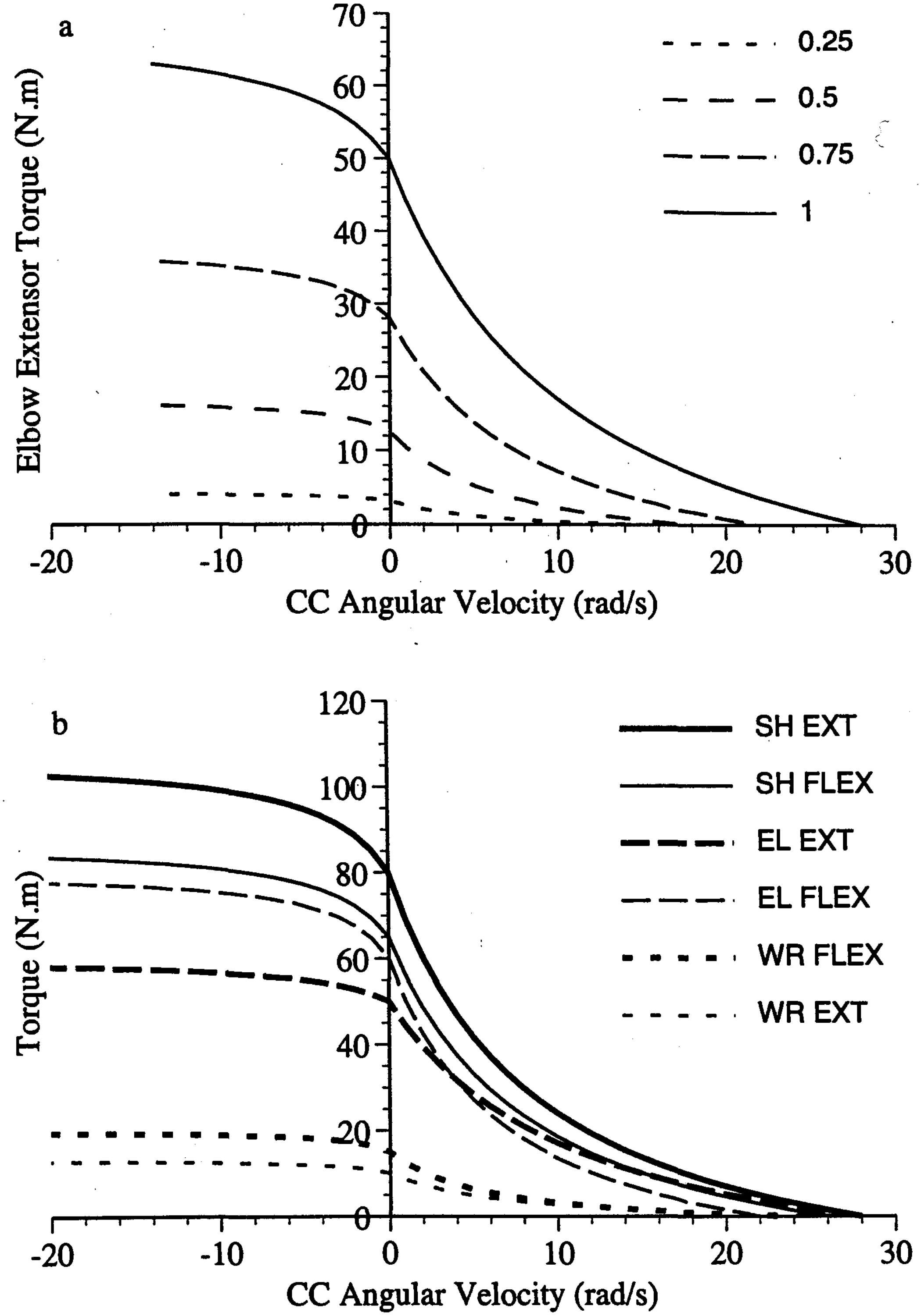


Figure M4. Torque-angular velocity relationship for (a) the elbow extensor at four levels of activation and (b) for all muscles at maximal activation.

2. *Series Elastic Component*

The series elastic component does not reside in any one anatomical structure. The sources for this elastic element are passive connective tissues, including the tendon and the z-disc structure within muscle fibres. There is also evidence that the myofilaments and cross-bridge structure are involved, indicating that the stiffness of this element is a function of activation, (Winters, 1985; Huxley and Simmons, 1971). The combined influence of these sources was described by the following exponential relationship:

$$MSEC = (K1SEC + ACT) \times \left(e^{(K2SEC \times \Delta\Theta_{sec})} - 1\right) \tag{5}$$

where

$$K1SEC = \frac{MMAX}{e^{SESH} - 1}$$

$$K2SEC = \frac{SESH}{SEXM}$$

where

$MSEC$: moment developed in the SEC
ACT: level of activation (on the interval <0,1>)

$\Delta\Theta\,\mathrm{sec}$: stretch in the SEC
$MMAX$: maximal isometric torque
$SESH$: shape constant
$SEXM$: angle of stretch of the SEC at which maximal torque is produced
$K1SEC$: constant
$K2SEC$: constant

Figure M5 depicts the SEC torque-angle relationship for all six muscles at maximal activation. The values of the parameters used to generate these relationships are given in Table M2.

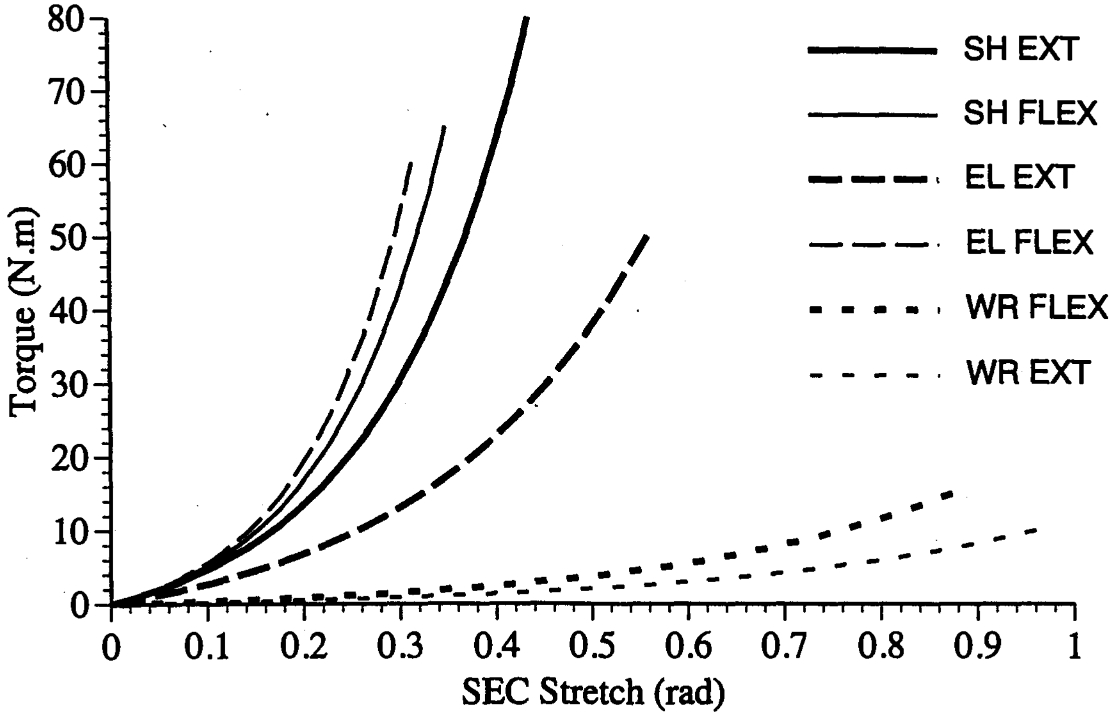


Figure M5. Relationship between stretch in the series elastic component (SEC) and torque developed in the SEC for all muscles at maximal activation.

3. Parallel Elastic Component

Parallel elasticity is due primarily to the passive tissue within and surrounding muscle. This includes passive connective tissue such as ligaments, fascia and anatomical bony constraints. Its influence is often excluded from muscle models because it develops force only at the extremes of range of joint rotation. However, due to the large angular excursions of the segments during throwing, this element was included in the current model. The equation representing the relationship between torque and angle for the PEC is:

$$MPEC = K1PEC \times \left(e^{(K2PEC \times \Theta)} - 1\right) + PESL \times \Theta \qquad (6)$$

where

$$K1PEC = \frac{\left(\frac{MMAX}{3}\right)}{e^{PESH} - 1}$$

$$K2PEC = \frac{PESH}{PEXM}$$

where

$MPEC$: moment developed in the PEC
$MMAX$: maximal isometric torque
$PESH$: shape constant
Θ: joint angle
$PESL$: linear constant
$PEXM$: angle at which maximal isometric torque is developed

Figure M6 indicates that the contribution of the parallel elastic component is minimal in the central region of joint range of motion, but increases near the extremes. Table M2 provides the values of the parameters which were used to generate these relationships.

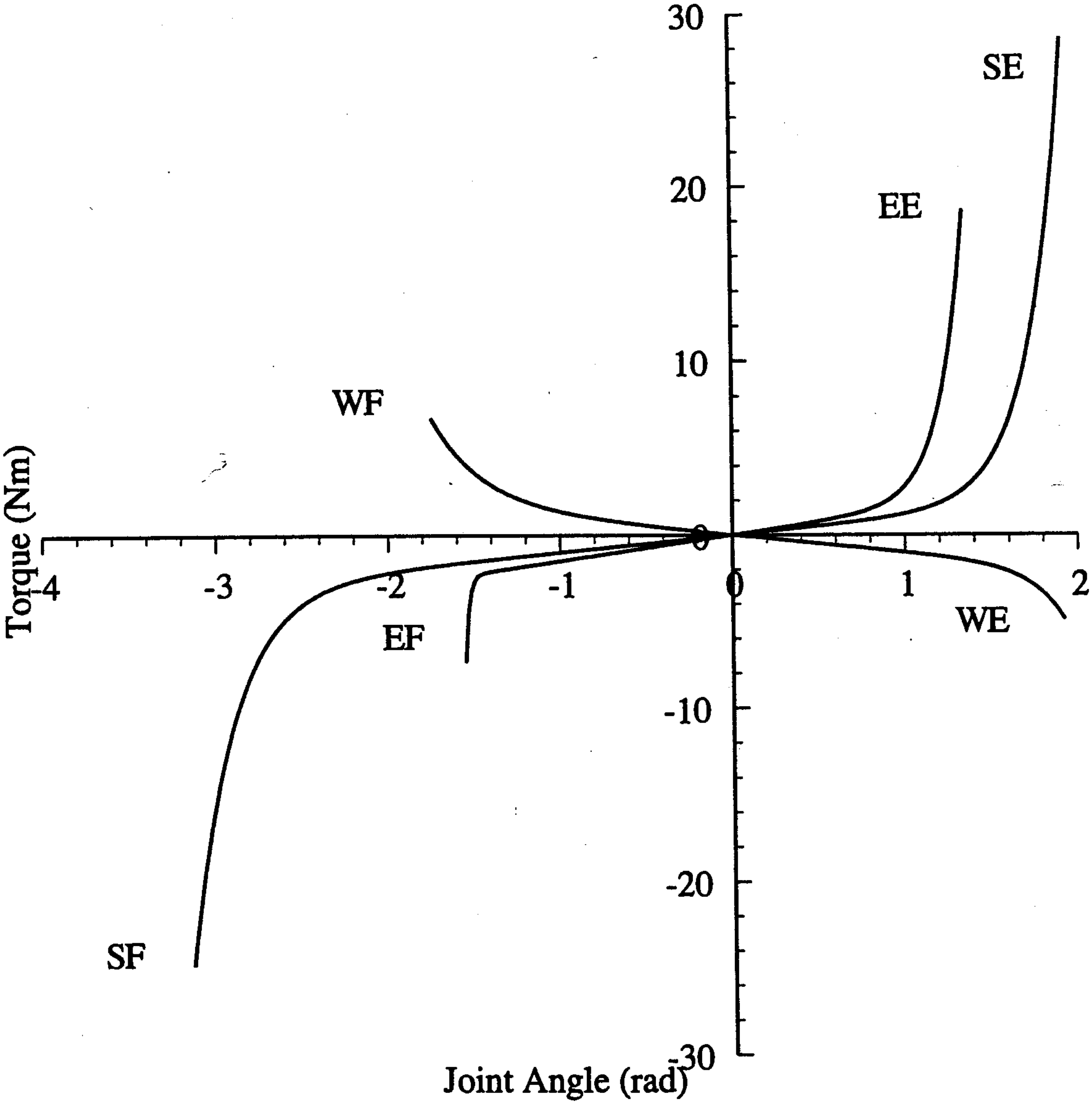


Figure M6. Relationship between torque developed in the parallel elastic component as a function of joint angle for all muscles.

4. Activation/Deactivation Dynamics

Force development in muscle requires activation from neural input. Neural stimulation from the central nervous system has been modelled as a simple exponential relationship with separate time constants for activation and deactivation. The process being represented is the temporal delay between the neural input and the contractile process, which is limited by calcium dynamics. Activation has been shown to be a more rapid process than deactivation. The level of activation can vary between 0 and 1, where a level of activation equal to 1 indicates maximal effort. The following equations were used to determine the level of activation at a given instant in time. An example of an activation profile for one muscle is shown in Figure M7.

Activation:

$$ACT = 1 - e^{\frac{(t-t_a)}{\tau_a}} \tag{7}$$

Deactivation:

$$ACT = e^{\frac{(t-t_d)}{\tau_d}} \tag{8}$$

where

ACT:	level of activation (on the interval <0,1>)
t:	current time
t_a:	time at which activation was initiated
τ_a:	activation rise time constant (0.005s)
t_d:	time at which deactivation was initiated
τ_d:	deactivation decay time constant (0.030s)

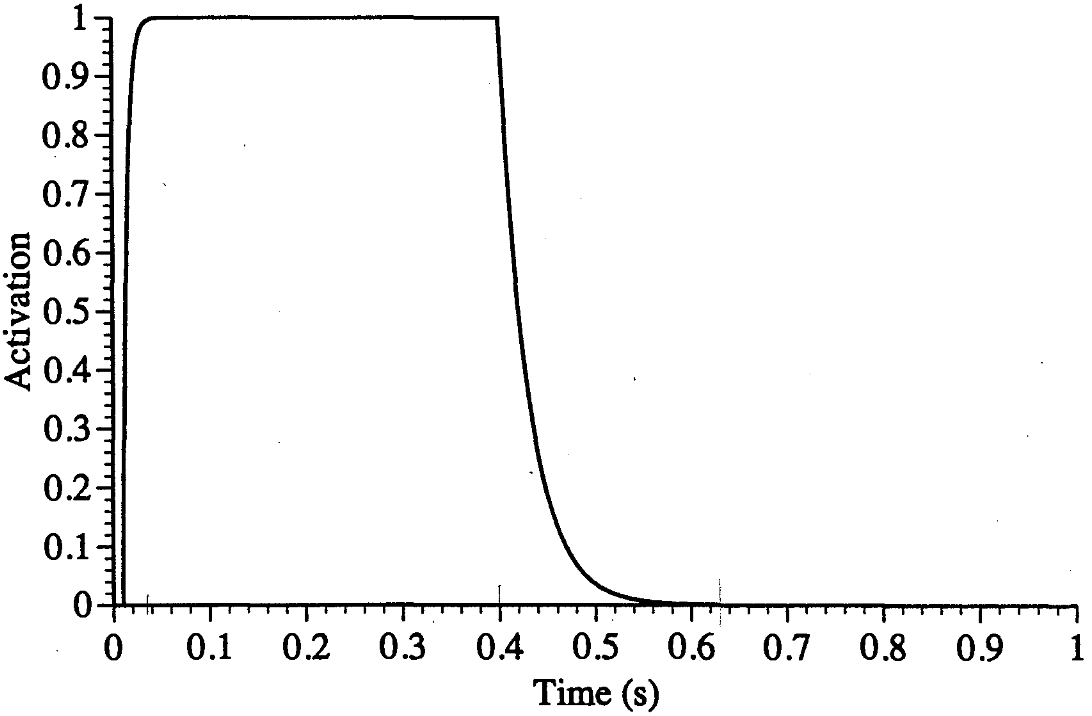


Figure M7. Activation profile used for all muscles. In this example, onset of activation was at 0.005s and deactivation was initiated 0.4s later.

5. Joint Viscosity

Frictional effects at the joints were modelled using linear passive viscosity. The values for the parameters used were 0.1, 0.2, and 0.25 Nms.rad^{-1} a at the shoulder, elbow and wrist, respectively.

The magnitudes of all parameters used in the preceding equations are presented in the following table. The "shape" factors (SESH, PESH, MXSH and MVSH) included in Winters' (1985) equations are used to define the amount of curvature or flatness in a particular relationship. A template was provided which consisted of a series of normalized relationships with different amounts of curvature. Each curve was labeled with a number which corresponded to the magnitude of the shape parameter. For example, in the torque-angle relationship of the parallel elastic component, the high magnitude of PESH for the elbow flexor (70) results in a strong concave-upward curve as compared to the relationship at the shoulder, which is a shallower curve.

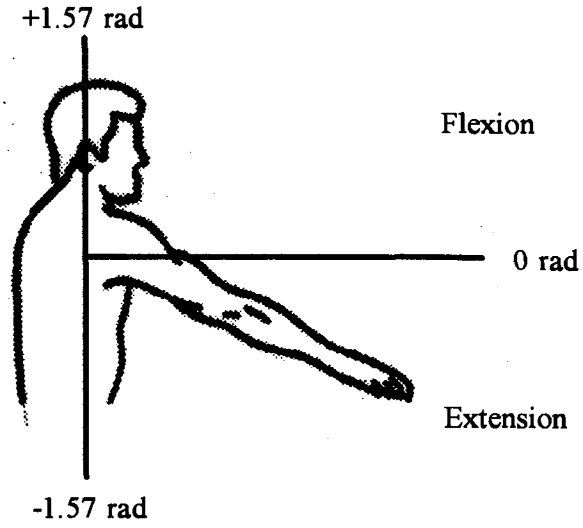
Table M2. Passive and active element parameters for each single equivalent muscle. Abbreviations of the parameters are explained in the text. The abbreviations of the muscles correspond to shoulder extensor (SE), shoulder flexor (SF), elbow extensor (EE), elbow flexor (EF), wrist flexor (WF) and wrist extensor (WE).

	SESH	SEXM (deg)	MMAX (N.m)	PESH	PESL	PEXM (deg)	MXOO (deg)	MXSH	MXSL	MVSH	MVVM (rad.s^{-1})
SE	2.80	25.0	80.0	10.0	1.0	110.0	25.0	4.0	0.00	0.31	28.0
SF	2.80	20.0	65.0	13.0	1.0	180.0	-20.0	3.0	0.01	0.33	26.0
EE	2.40	32.0	50.0	10.0	1.5	77.0	-23.0	2.5	0.00	0.40	28.0
EF	2.80	18.0	60.0	70.0	1.5	87.0	10.0	2.1	0.01	0.32	22.0
WF	2.90	50.0	15.0	6.0	1.0	100.0	-10.0	2.0	0.00	0.25	23.0
WE	2.90	55.0	10.0	10.0	1.0	110.0	10.0	2.0	0.00	0.25	28.0

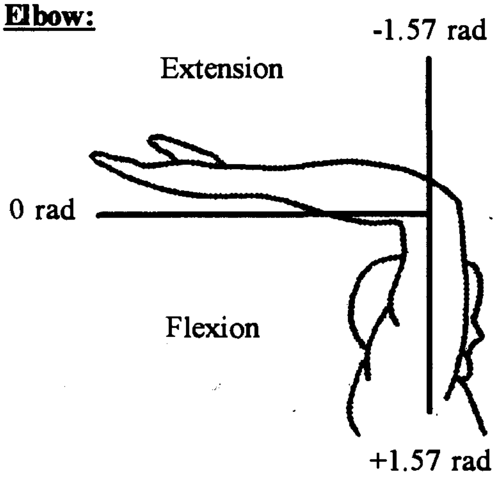
Constants:
MVER = 0.50
MVSHL = 0.50
MVML = 1.30

The angular conventions used to define the joint angles used within these equations and in Table M2 are given in Figure M8.

Shoulder:



Elbow:



Wrist:

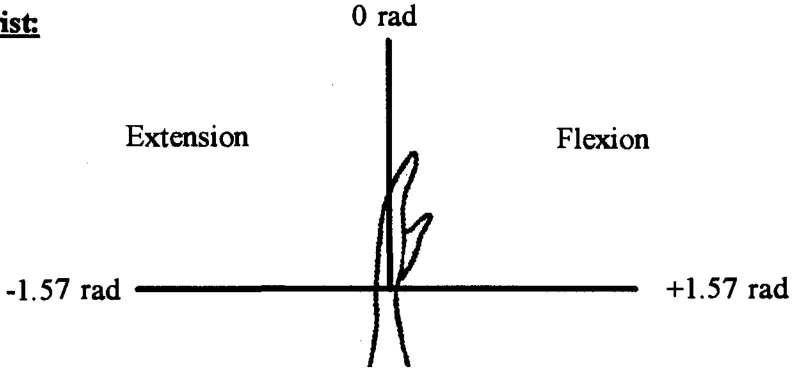


Figure M8. Joint angular conventions used to define relationships used in all muscle models.

II. THE MUSCLE MODEL

The magnitude of the muscle moments at each joint were generated by an iterative process which incorporated all of the muscle relationships described in the previous section as well as the joint kinematics of the three-segment linkage. Once the muscle moments were calculated at a given instant in time, they were input into the equations defining the mechanics of the system so that the external kinematics at the next point in time could be determined. These were in turn used to begin the process again, whereby the muscle moments at the next time step were calculated based on the new kinematics. The iterative procedure used is similar to that used by Baildon and Chapman (1983) and Caldwell (1987) and is outlined in Figure M9.

Figure M9 describes how the torque-time relationship of one single equivalent muscle is developed. At zero time, the initial conditions of the level of activation, joint angle and joint angular velocity must be known. If activation has not been initiated, then the contractile component (cc) kinematics are the same as those of the joint (jt), i.e. $\Theta cc=\Theta jt$ and $\dot{\Theta} cc=\dot{\Theta} jt$, and no torque will be actively developed. After the onset of activation, torque will be produced by the contractile component. The first stage in the iterative loop defines the magnitude of the torque in the contractile component (Mcc) as equal to that of the series elastic component because the two elements are in series. The torque developed in the SEC is a function of the magnitude of SEC stretch ($\Delta\Theta sec$), where $\Delta\Theta sec=\Theta cc-\Theta jt$. The torque developed in the parallel elastic component is simply a function of joint angle, Θ. The total torque developed in the muscle is the sum of the torque generated by the contractile component and the torque developed in the passive parallel elastic component.

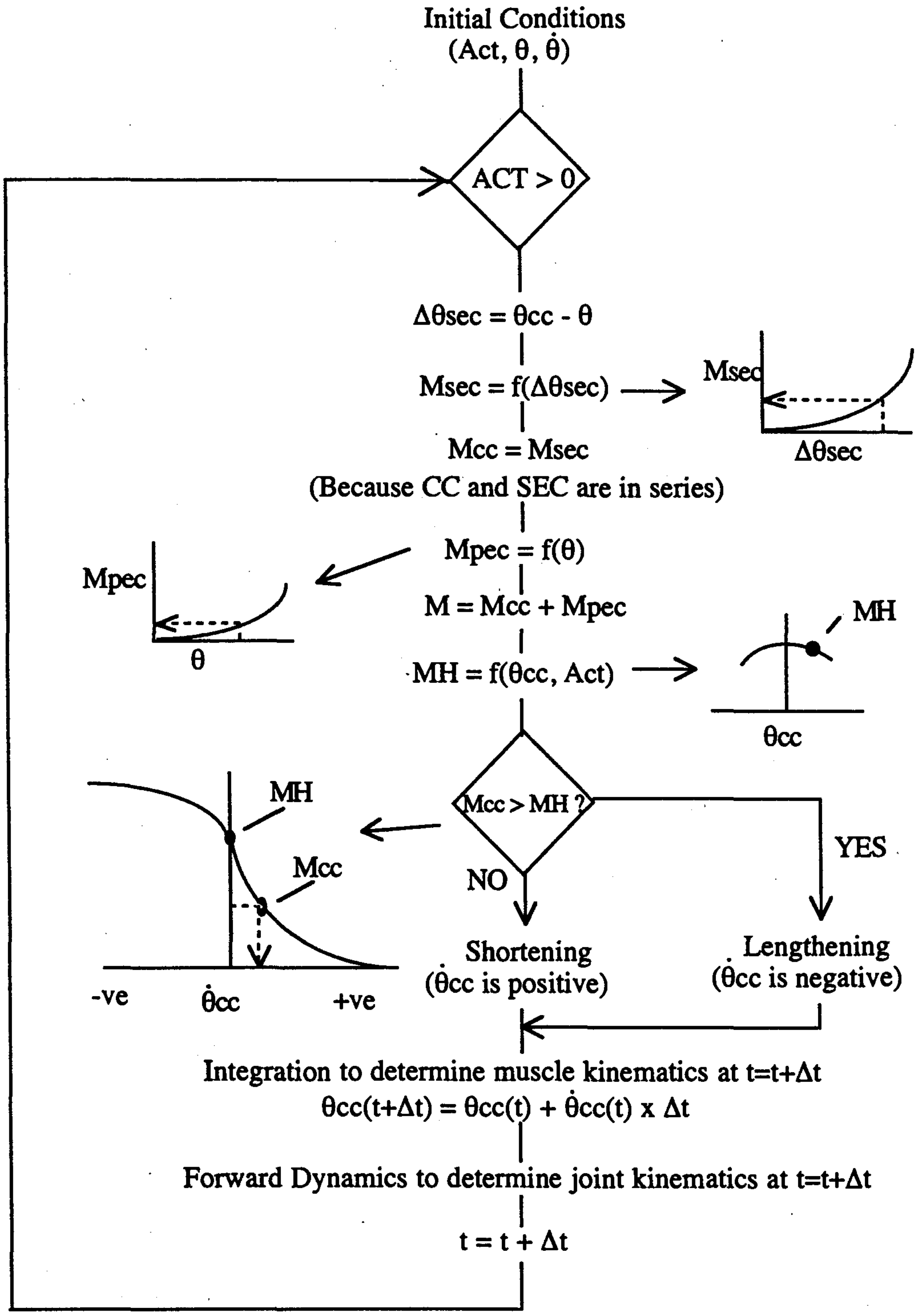


Figure M9. Iteration loop defining how muscle torques are developed. Explanation is provided in the text.

The remaining stages in the iterative loop are concerned with determining the kinematics of the muscle model elements and the joint angular kinematics. Because the torque produced by the contractile element is known (Mcc), it is possible to determine the angular velocity of the CC associated with this torque, provided that the isometric torque is known for the current angle of the contractile element and level of activation, (i.e. MH in Figure M9). A comparison is made between Mcc and MH. If Mcc is less than the isometric torque, MH, then the contractile component is shortening and $\dot{\Theta}$cc will be positive, according to the defined torque-angular velocity relationship. On the other hand, if Mcc is greater than the isometric torque, MH, then the contractile element is lengthening and $\dot{\Theta}$cc will be calculated to be negative. Once these steps are completed, the muscle torque and the kinematics of the muscle model elements are known. The magnitude of the muscle torque is used to determine the joint angular kinematics of the segmental model at the next instant in time through forward dynamics. Integration is also used to calculate Θcc at the next instant in time in order that the iterative process can resume at $t=t + \Delta t$.

An example of the torque generating behaviour of the elbow extensor muscle model during an isometric contraction and a concentric contraction from rest is shown in Figure M10. In both contractions, activation was initiated at 0.05s and remained maximal until 0.20s, at which time, deactivation began. The elbow joint was fixed at a neutral angle of -0.4 rad (using the angular convention shown in Figure M8) during the isometric contraction. During the concentric contraction, the forearm started at the same angle, then rotated relative to the stationary upper arm. During the contraction, an inertia of 3.0kg.m^2 was rotated. An example of a stretch-shortening contraction is also shown in Figure M10. The initial velocity of the forearm was -2rad.s^{-1} and the activation profile was the same as that used in the previous contractions.

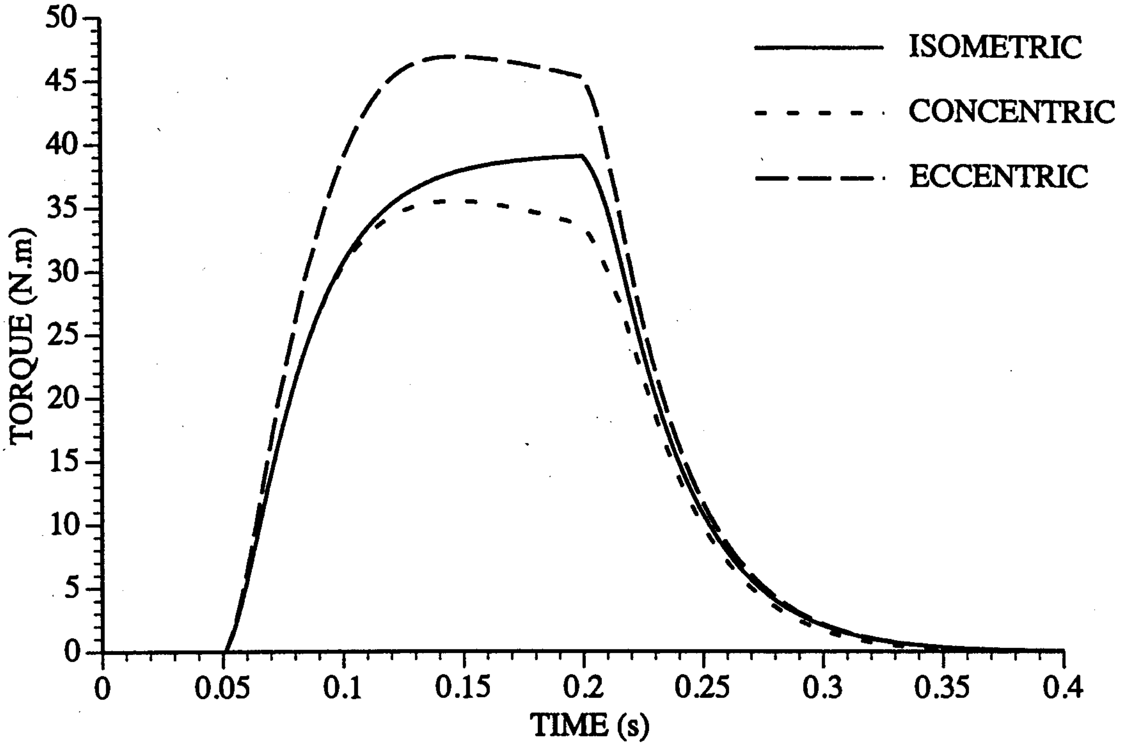


Figure M10. Torque profiles of the elbow extensor muscle model during isometric, concentric and stretch-shortening contractions. Activation was initiated at 0.05s and deactivation was initiated at 0.20s.

III. GENERATION OF A SIMULATED THROW

Each throw was initiated with the limb segments in the same configuration each time and with an initial angular velocity of zero. The arm began in an almost fully extended position in the vertical direction. The initial angles at the shoulder, elbow and wrist were 0.087, -0.175 and -0.262 radians, respectively. A throw was produced by activating each muscle at a specified time. The magnitude of the torque developed by each muscle model depended on the level of activation and the kinematics of the system. Once the magnitudes of the muscle moments were calculated, a forward dynamics approach was used to determine the influence of the torques on the dynamics of the system at intervals of 1 ms. This process was repeated whereby the muscle models at each joint took into account the new kinematic parameters and generated a new torque which acted upon the segments to move them to their next position.

The equations of motion for the mathematical model were written using Lagrangian formalism, and are presented in Herring (1989). The use of forward dynamics involves a set of second order non-linear differential equations which cannot be solved analytically. This problem requires that numerical techniques be used to approximate the solution to the equations of motion. An integration subroutine, LSODI, was used to make the approximations (Bader and Deuflehard, 1983). The main simulation program, THROW, and the LSODI subroutine were written in Fortran77 programming language.

The objective in developing this model was to include segmental and muscular properties that were physiologically similar to those in humans. It was expected that if this were the case, then the behaviour of the system would also be similar to human behaviour. In spite of these efforts, there were some throws in which the joint ranges of motion went beyond those which are physically possible without causing injury, or in which the torques generated were above maximal levels. The range of motion and muscle torque limits which were imposed on the model to constrain its behaviour are given in Table M3. The magnitude of the maximal torques used to constrain the model are greater than the maximal torques (MMAX) presented in Table M2. The reason for the difference is that MMAX represents the maximal isometric torque that can be developed; whereas, the maximal torques given in Table M3 take into account the fact that (i) muscles can produce torques greater than MMAX during eccentric contractions and (ii) the torque developed in the parallel elastic component is additive with that generated in the contractile component. In simulations in which these limits were exceeded, the throw was defined as unacceptable and was discounted.

Table M3. Constraints placed upon joint range of motion and magnitude of torque generation in a simulated throw. The joint angular convention corresponds to Figure M1.

	MAXIMAL MUSCLE TORQUE (N.m)	JOINT ANGLE LIMIT (rad)
SHOULDER EXTENSION	190.0	3.7
ELBOW EXTENSION	115.0	0.0
WRIST FLEXION	35.0	1.74
SHOULDER FLEXION	170.0	-0.70
ELBOW FLEXION	140.0	-2.91
WRIST EXTENSION	23.0	-1.70

The performance criterion used to evaluate the success of each acceptable throw was the horizontal distance that the ball was projected from the point in the hand from which it was released. This objective is not representative of all throwing tasks performed by humans. In some throwing activities, the goal is to throw as fast as possible and in others, accuracy may be an important contributor to success. However, the goal of maximal ball range was chosen for this model because it combines the criteria of having to maximize velocity and optimize the orientation of the limb so that the velocity vector of the ball at release is in an optimal direction for the given configuration of the arm at release. The criterion of maximal velocity was not chosen for these simulations for several reasons. Firstly, maximizing velocity in throwing is useful only if the ball is projected in a desirable direction. While the simulations could have been constrained so that throws with undesirable release angles (i.e. backward or downward) were eliminated, the actual coordinates of release of the ball from the hand could not be constrained. The height of release and orientation of the hand could be considered to be confounding factors when trying to optimize performance, but in actual throwing conditions, these are factors that do contribute to success, therefore, it is important to include them in efforts to optimize the behaviour of the system. Lastly, the projected distance of an object is influenced most by release velocity and less by the height and angle of release.

In each individual simulation, a predetermined number of iterations was carried out. Joint positions and velocities at each time step were stored and subsequently used to calculate how far the ball would be projected, were it to leave the hand at that time step. The data were then evaluated to determine which position of the arm at release led to maximal ball range. Again, if the limits imposed on the joint torques or joint ranges of motion were exceeded prior to ball release, then the throw was excluded.

IV. SIMULATION SCHEME

The algorithm describing the method by which a single throw is simulated has been explained previously. In order to meet the objective of finding those throws which project the ball the greatest distance under the conditions described above, the following strategy was implemented. Specific boundaries were used to define a large region of possible throws. Once all throws within the specified region had been generated, the results were inspected and the throw which produced maximal performance was identified. If, in any case, maximal performance was produced by a throw at the limit of the established boundaries, then the search field was extended and additional throws were simulated until no further improvements were observed.

The boundaries were defined by onset times of activation and deactivation of the three antagonistic and three agonistic muscle models. In the majority of simulated throws, the agonists, once activated remained fully active until the completion of the throw. Therefore, there were nine onset times which were defined in order to generate a throw: three agonist activation times, three antagonist activation and three antagonist deactivation times.

A large number of simulated throws within a specified search field was produced by systematically varying these times, and will be referred to as a "batch" for the remainder of this thesis. An example of the boundaries used to define a batch file is described below. The time of onset of the three agonists was varied in 20ms increments starting from time 0.020s up to 0.340s, where 0.000s is defined as the start of a throw. All possible combinations of times of onset of the agonists within these boundaries were simulated. An example of how a series of throws is generated is shown below. The three numbers within each set correspond to the time of onset of the shoulder, elbow and wrist agonsits, respectively.

0.020 0.020 0.020	0.020 0.040 0.020	...	0.260 0.280 0.020	...
0.020 0.020 0.040	0.020 0.040 0.040	...	0.260 0.280 0.040	...
0.020 0.020 0.060	0.020 0.040 0.060	...	0.260 0.280 0.060	...
0.020 0.020 0.080	0.020 0.040 0.080	...	0.260 0.280 0.080	...
⋮	⋮		⋮	

This procedure resulted in a total of 4,913 simulated throws. In addition, the times of onset of antagonistic activation and subsequent deactivation were specified for each possible throw. Each change to the search field used to define the temporal pattern of antagonist activation necessitated the re-simulation of each of the previously defined agonistic onset times. If, for example, the duration of activation of the shoulder flexor was increased from 0.100 to 0.200 seconds, then the total number of simulated throws would double to 9,826.

The number of possible combinations of times of onset of activation and deactivation is endless. Due to the limited disk space on the computer, it was not possible to simulate every combination of onset times in a single batch. Therefore, a systematic approach was used whereby a number of search fields were used to define regions of success, (i.e. throws in which the ball was projected a greater distance than in other throws). Subsequent simulations narrowed down the regions of success until eventually one optimal solution was found.

In the following two sections, this method of using repeated batches of simulated throws was used to identify the optimal throw under the condition of interest. In the first case (Chapter 3), antagonists were activated at the beginning of the throw to induce a backswing, but were deactivated and remained so for the remainder of the throw. In the second condition (Chapter 4), the effect of proximal antagonism near the end of the simulated throw was investigated. In the final chapter (Chapter 5), modifications were made to the parameters used to describe the mechanical characteristics of muscle, and the influence on throwing performance was determined.

Chapter 3. Optimization of Throwing

METHODS 1

GENERAL OVERVIEW

A multi-stage protocol was used to generate the throw which projected the ball a maximal distance. This throw, once identified, is defined as the optimal throw. During each stage, a series of search fields was established in which many throws were generated. The boundaries of each search field were defined by the time of onset of activation and deactivation of each muscle model and the throw which projected the ball a maximal distance within each was identified. Initially, global search fields, comprising a large number of throws were used. In these global searches, the times of muscle onset were distinguished by large time increments (e.g. 0.020s). Once regions of success (i.e. greater projected distances of the ball) were identified within the global search field, a fine-tuning approach, using smaller time increments (0.005s), was utilized to home in on a local best throw. This process whereby a global search field was used to narrow down a general region of success followed by a fine-tuning of the activation onset times was repeated several times. Ultimately, any further modification to timing brought about no improvement in performance. Only those acceptable throws, in which the criteria for inclusion were met, are considered in the results. Within these acceptable throws, some are more successful than others, as defined by the projected distance of the ball.

In the first search fields that were generated, the optimal antagonistic temporal profiles during the early stages of the throw were identified. These antagonistic torques were required at the beginning of the throw to establish suitable backswing conditions for the model. Once these were identified, further searches were used to find the optimal onset times of the three agonistic muscles. The torque profiles produced by the agonists were responsible for the forward motion of the three segments.

Identifying the optimal temporal pattern of antagonistic activity was complicated because a number of variables had to be considered. Several batch files of simulated throws were generated in order to identify: i) the optimal time of onset, and ii) the duration that each antagonistic muscle remained active prior to deactivation. Once a region of successful activation and deactivation times of the antagonists was established, the second stage was carried out. In this second stage, a systematic search for the optimal times of onset of the three agonistic muscles was executed. The two stages were not mutually exclusive because the choice of antagonistic time profiles dictated, in part, the agonistic onset times which would generate a successful throw. In sum, the goal was to establish a single set of times which, together, would generate the optimal throw. This set of times included a time of activation and deactivation for each of the antagonists, and onset times for each of the agonists. Once activated, the agonists were not deactivated.

STAGE I

GENERAL TIMING OF ANTAGONISTS (Part 1)

The configuration of the three arm segments at zero time was such that in the absence of any muscle activity, the arm collapsed in the forward direction. To avoid this, it was assumed that shoulder flexor activity was necessary for all successful throws. On the other hand, there was no reason to believe *a priori* that antagonistic activity at the elbow and wrist was essential for a successful throw. Therefore, the purpose of the first series of simulations was to determine systematically if activation of all antagonists was necessary for optimal performance.

In this stage, as well as determining if activation of all antagonists was necessary for generating a successful throw, an initial estimate was made of the optimal duration of activation of each of the antagonists. A series of simulations was carried out in which the effect of short, medium and long durations of activation on throwing performance was investigated. For simplicity, antagonistic activity was initiated at zero time (0.000s) in all throws, and continued for either 0.050, 0.100 or 0.125 seconds.

These two objectives (i.e. which antagonists should be activated and for what duration) were met by executing nine batches of simulations. They were set up in the manner shown in Table M1-1. Each batch of simulations is labelled SHORT, MEDIUM or LONG, denoting whether the duration of activation of the antagonists was 0.050, 0.100 or 0.125s. The ON and OFF labels indicate whether or not each antagonist was activated. In this first stage, two restrictions were placed on the behaviour of antagonistic activity. In those simulated throws in which antagonism was used, activation of the antagonists always began at zero time. Secondly, when antagonism was used at more than one joint, the duration of activation was the same for all muscles. This simplified the process and resulted in only a gross estimation of the optimal antagonistic activation patterns.

Table M1-1. Combinations of antagonistic onsets and durations. When antagonism was used, it was initiated at zero time.

BATCH	SHOULDER FLEXOR	ELBOW FLEXOR	WRIST EXTENSOR	DURATION (s)
SHORT1	ON	ON	ON	0.050
SHORT2	ON	OFF	OFF	0.050
SHORT3	ON	ON	OFF	0.050
MEDIUM1	ON	ON	ON	0.100
MEDIUM2	ON	OFF	OFF	0.100
MEDIUM3	ON	ON	OFF	0.100
LONG1	ON	ON	ON	0.125
LONG2	ON	OFF	OFF	0.125
LONG3	ON	ON	OFF	0.125

Each of the antagonistic profiles defined in Table M1-1 were used in conjunction with a set of agonistic onset times which comprised a global search field. The time of onset of the shoulder extensor, elbow extensor and wrist flexor muscles was varied from 0.020 seconds to 0.340 seconds by increments of 20 ms, where 0.000s is defined as the start of the throw. Simulated throws were produced for all possible combinations of onset times within these boundaries, resulting in 4,913 throws in each of these nine batches. For example, the first throw generated in the batch labeled SHORT1 had the following combination of activation and deactivation times (s):

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.020	0.020	0.020	0.000	0.000	0.000
DEACT:	------	------	------	0.050	0.050	0.050

Similarly, the final throw in the same batch of simulations was generated with the times shown below:

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.340	0.340	0.340	0.000	0.000	0.000
DEACT:	------	------	------	0.050	0.050	0.050

The throws generated in the nine batches of simulations produced in Part 1 were evaluated in terms of the distance the ball was projected from the hand. The times of onset of the three agonists responsible for the most successful throw in each batch were recorded for future reference in Part 2. For example, the best throw in SHORT1 was generated when the shoulder, elbow and wrist agonists were activated at times 0.200, 0.280 and 0.300 seconds, respectively.

GENERAL TIMING OF ANTAGONISTS (Part 2)

The purpose of Part 1 was to identify successful and unsuccessful antagonistic temporal patterns in order to establish the best localized region to search for the optimal throw. In general, the throws simulated in Part 1 produced greater ball ranges when the antagonists were activated for long or medium durations rather than short durations. The second finding was that the poorest throws occurred when there was no antagonism at the elbow and wrist joints. However, the difference in magnitude of the ball range of the best throw from each of the nine batches in Part 1 was minimal (2.4 m). The best throw was from LONG3 and had a range of 14.14m, compared to the poorest which projected the ball a distance of 11.74m in SHORT2. This difference was not believed to be substantial enough to warrant the elimination of any of the antagonistic activity patterns tested in the Part 1 trials from the next phase. Therefore, prior to proceeding with the search to find the optimal antagonistic activation patterns, the agonistic temporal patterns of the most successful throws in each of the batches in Part 1 were revised.

The best throws from each of the nine batches in Part 1 underwent the following refinements. Because the times of onset of the agonists which generated maximal ball range were identified previously, the breadth of the search field used in subsequent simulations was reduced significantly. That is, once a local region of successful temporal patterns was identified, it was not neccessary to simulate throws using temporal patterns which previously proved to be unsuccessful. In addition, the increment of time used to distinguish between throws was reduced from 20ms to10ms.

The results from these simulations were used to identify the best throw in each of the nine batch files. The maximal ball range occurred in LONG3, indicating that long durations of shoulder and elbow antagonistic activity at the beginning of the throw were desirable. The times of onset of the shoulder, elbow and wrist agonists which resulted in optimal performance were: 0.200, 0.300 and 0.320 s, respectively. The ball was projected a distance of 14.14 m.

STAGE II
SPECIFIC TIMING OF ANTAGONISTS

The results from the simulations in the previous stage were used to dictate the direction of the next series of simulations. Having established the new search field in terms of agonistic onset times, i.e. in the region of 0.200, 0.300, 0.320s, the remaining refinements were concerned with establishing a more precise optimal antagonistic temporal pattern.

Antagonistic onset times and durations

The first purpose was to determine whether throwing performance could be enhanced by activating the antagonists at times other than time zero. The second purpose was to determine the effect of using durations of activation other than those previously used (i.e. 0.050, 0.100 and 0.125s). The final modification was to have the shoulder, elbow and wrist antagonists remain active for durations which differed from each other.

These objectives were met by using the same approach discussed earlier whereby large searches were used to identify global maxima after which, local searches about identified maximal throws were performed. In this case, the primary interest was in optimizing the antagonistic activity patterns. Therefore, the time increments used to define antagonistic onset times and durations were small. On the other hand, there was only a general interest in the effect of agonistic timing. The only concern in relation to agonistic activity was that the times used were in a previously defined region of success. As a result, large increments of time were used (0.020s) to distinguish between agonist onset times.

Shoulder and elbow antagonism

Because the results from the previous stage indicated uncertainty regarding the influence of the wrist extensor to successful throws, the present investigation focussed on the identification of optimal behaviour of the shoulder and elbow antagonists. A large batch file was generated in which the shoulder and elbow antagonist onset times included 0.000, 0.025 and 0.050s. In addition, different durations of antagonistic activity were also used. Once activated, the antagonists remained on for durations of either 0.100, 0.150, 0.200 or 0.250 seconds.

The results indicated that throwing performance was more successful when the shoulder and elbow antagonists were activated at zero time. The durations of shoulder and elbow activation which consisently produced the best results were 0.100 and 0.200s, respectively. Maximal ball range (14.16m) was generated in the throw with agonistic onset times of 0.190, 0.260 and 0.280 s at the shoulder, elbow and wrist, respectively.

Wrist antagonism

Keeping the agonist onset times constant and equal to those associated with the best throw, (i.e. 0.190, 0.260 and 0.280), the times of activation and duration of the wrist antagonist were manipulated. Thirty-six possible wrist extensor temporal patterns are detailed in Table M1-2. The shoulder and elbow antagonists were always activated at zero time and remained active for a duration of 0.100 and 0.200s, respectively.

Table M1-2. Times of activation and duration for throws in Batch FINE1.

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.190	0.260	0.280	0.000	0.000	0.025
						0.050
						0.075
						0.100
						0.125
						0.150
DURATION:	------	------	------	0.100	0.200	0.050
						0.100
						0.150
						0.200
						0.250
						0.300

The results from Batch FINE1 indicated that optimal performance resulted when the wrist antagonist was activated at 0.100 s. However, successful throws were also generated by activating the wrist extensor at 0.050 or 0.150 seconds. The most successful throws occurred when the duration of wrist antagonism was either 0.100, 0.150 or 0.200 seconds.

Combination of Antagonist and Agonistic Timing

Having previously identified the optimal antagonist profiles for the shoulder and elbow and having currently narrowed down the possible temporal patterns for the wrist, the subsequent batch of simulations was formulated to determine the interdependent nature of the wrist antagonistic activity on the agonist times used in the simulated throws.

The next large batch of throws allowed 216 possible combinations of agonist onset times over the range of:

SHOULDER EXTENSOR	ELBOW EXTENSOR	WRIST FLEXOR
0.150	0.240	0.270
↓	↓	↓
0.200	0.290	0.320

with intervals of 0.010 seconds between each. The shoulder and elbow antagonists were activated at time zero in all throws, and were deactivated after 0.100 and 0.200 seconds, respectively. The wrist antagonist was activated at either 0.050, 0.100 or 0.150 seconds, and remained on for a duration of either 0.050, 0.100 or 0.150 seconds. The optimal throw (14.586m) was produced by the following activation and deactivation time profiles:

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.200	0.280	0.270	0.000	0.000	0.100
DEACT:	------	------	------	0.100	0.200	0.250

The times which produced the previous best throw were fine-tuned in the final batch of throws was in order to do the final stage of the search for the optimal throw. The following onset times and durations were used to generate 2187 throws:

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.195	0.275	0.265	0.000	0.000	0.050
	0.200	0.280	0.270			0.100
	0.205	0.285	0.275			0.150
DURATION:	------	------	------	0.075	0.175	0.150
				0.100	0.200	0.200
				0.125	0.225	0.250

RESULTS 1

The results are divided into two sections. Firstly, a general overview of the nature of successful throws compared to less successful throws will be presented. In doing so, those variables which are significant contributors to maximal throwing performance are indicated. After addressing the general mechanisms of successful throwing, the results from the maximal range throw follow. This allows a detailed analysis of the exact nature of optimal performance.

I. Sub-Optimal Throws

In this section a comparison is made of the results from a subset of throws which were produced during the series of simulations which led to the identification of the optimal throw. These throws are defined as sub-optimal because, in all cases, the distance that the ball was projected was less than that of the ultimate best throw. Each of these throws began with the antagonists being activated at zero time and remaining active for 0.05, 0.10 and 0.15s at the shoulder, elbow and wrist, respectively. Agonistic activity was initiated at all possible combinations of the times shown in Table R1-1. Once activated, the agonists remained maximally activated for the duration of the throw.

Table R1-1. Times of agonistic onset for throws used to generate sub-optimal throws.

SHOULDER EXTENSOR (s)	ELBOW EXTENSOR (s)	WRIST FLEXOR (s)
0.050	0.100	0.150
0.100	0.125	0.175
0.150	0.150	0.200
0.200	0.175	0.225
	0.200	0.250
	0.225	0.275
	0.250	0.300
	0.275	0.325
	0.300	0.350

These simulations produced a batch of 324 throws, ranging in success from 3.95 to 13.24 metres. Of these throws, 201 were excluded from further analysis because the limits of acceptable joint range of motion were exceeded. The distance the ball was projected in the remaining 123 acceptable throws ranged from 5.9 to 13.24 metres. This group of sub-optimal throws did not include the ultimate optimal throw because the times of onset did not undergo the fine-tuning process required of the optimization process. However, the observations made with respect to this group of sub-optimal throws are of a general nature and can be applied to throws which were not included.

Each throw within the group of sub-optimal throws was analyzed in terms of energy, work and power. Each parameter was in turn plotted against ball range in order to highlight the distinguishing features between successful and unsuccessful throws. For comparison, successful throws are defined as those in which the ball was projected a distance greater than 12m and in unsuccessful throws the ball was projected less than 8m. These qualitative definitions were made to assist with the interpretation of the subsequent results. The equations used to calulate the kinematic and kinetic parameters presented in the results are found in Appendix B.

Energy and Work:

In successful throws, the hand segment gained considerable energy prior to ball release. During the same time interval, the energy in the upper arm was decreasing. To illustrate the importance of these changes in segmental energy in producing a successful throw, the following calculations were made. During the time between the occurrence of peak energy of the upper arm and ball release, the decrease in upper arm energy and the increase in hand energy were calculated. The relationship between these two values and performance is shown in Figure R1-1. Greater ball ranges are associated with a greater

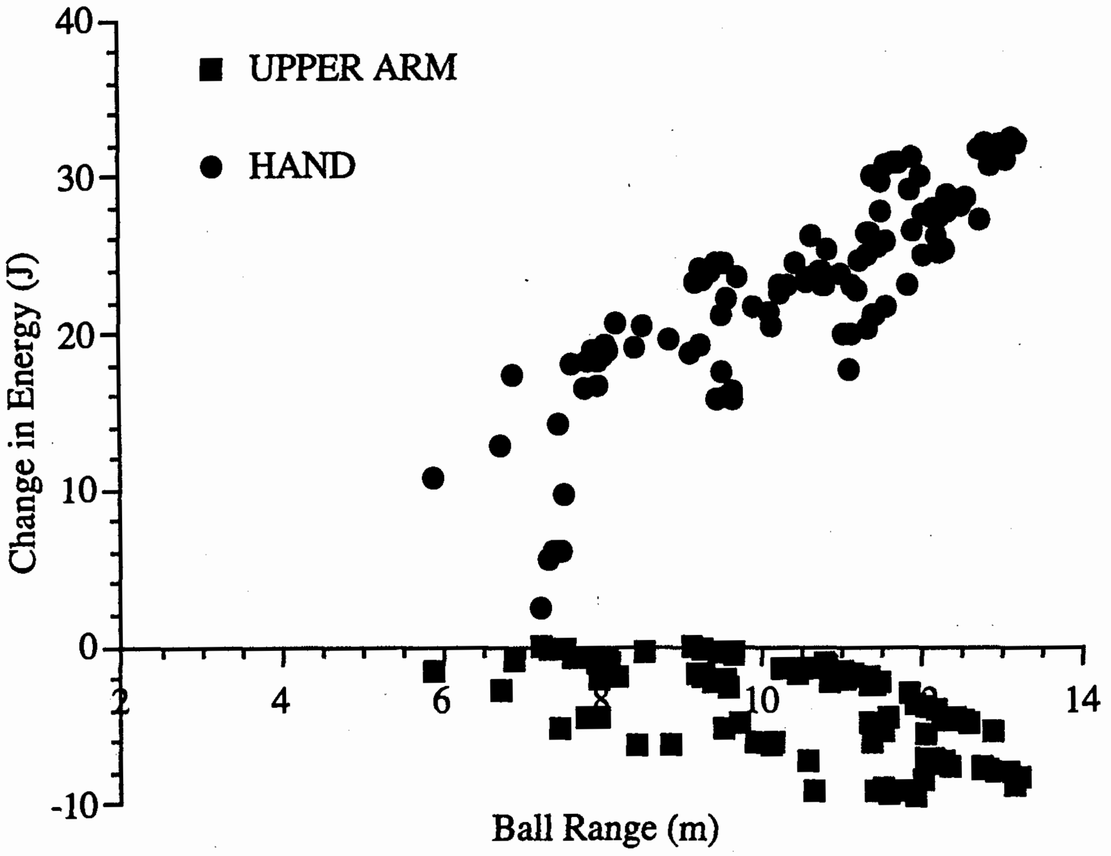


Figure R1-1. Change in total energy of the upper arm and hand segments vs ball range for 123 sub-maximal throws. Details regarding calculation are explained in the text.

decrease in upper arm energy with a concurrent greater increase in energy of the hand segment.

The association between the positive work done by each agonist and performance is shown in Figure R1-2. The contribution of each muscle to the total positive work done is expressed as a fraction of the total positive work and plotted against ball range. There is no association between the amount of work done by the wrist flexors and ball range. The relationship between the work done by the two proximal muscles and ball range is complex. It is evident that maximal performance is not achieved by maximizing the work done by either of these muscles. Rather, performance is maximized by some intermediate amount of work done by the shoulder and elbow extensors. The open symbols in Figure R1-2 show the results for seven selected throws. They indicate that when high levels of work are done by the shoulder, the work done by the elbow is minimal. Likewise, when the work done by the elbow is near maximal, that of the shoulder is reduced. Therefore, maximal performance results when some intermediate level of work is done by the shoulder and the elbow.

The work done by each muscle is the integral of the torque with respect to change in joint angle. In order to determine if the observed relationship between ball range and work done is accounted for by the range of motion through which each joint rotates, or by the torque producing capabilities of the muscles, these two variables were plotted against ball range (Figures R1-3a and R1-3b). Joint range of motion was defined as the difference in joint angle between the most flexed and most extended positions during the time prior to ball release. The variable used to represent the torque producing capabilities during the throw was peak torque. The results show that the nature of the relationship between joint range of motion and ball range (Figure R1-3a) closely resembles that in Figure R1-2, although the magnitude of joint angular excursion at the elbow is greater than at the shoulder. At first glance, it appears that there is little correlation between peak torque at a particular joint and projected range of the ball (Figure R1-3b). The relationship is

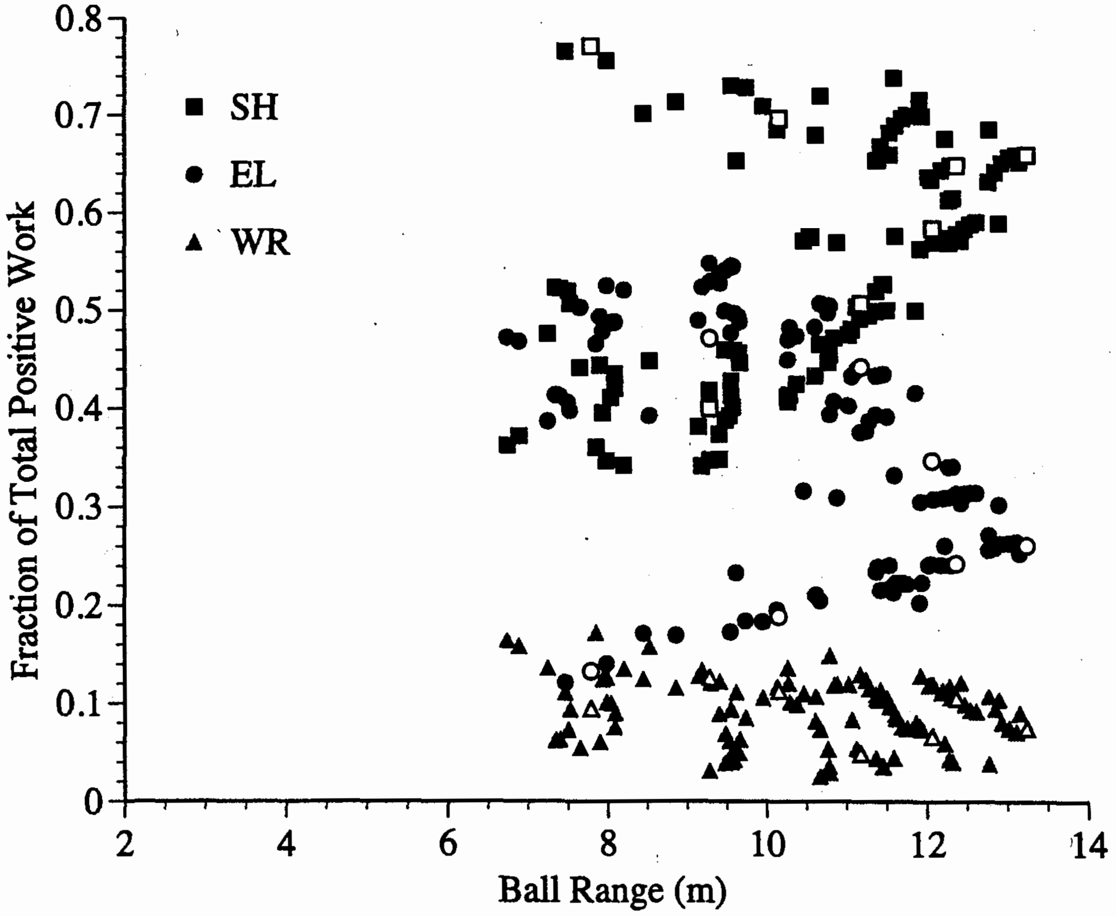


Figure R1-2. Fraction of total positive work done by the shoulder, elbow and wrist (SH,EL,WR) agonists vs ball range in 123 sub-maximal throws. Significance of open symbol is explained in the text.

complicated, as there are throws in which equally poor performance was associated with both high and low peak agonist torques at the shoulder.

These results indicate that there is a complex interaction of factors which combine to produce the resulting performance. For example, one of the poorest throws (open symbol in Figures R1-2 and R1-3 at 8m) occurred when maximal shoulder work was done; however, in this same throw, minimal work was done by the elbow extensors. This illustrates the need for optimal timing of muscle onset in order that the conditions are favourable at all joints. The decrement in performance in this throw appears to be due to the low magnitude of the peak shoulder torque (Figure R1-3b), even though the shoulder rotated through a large range of joint motion (Figure R1-3a). The torque producing capability of a muscle is largely dependent upon the joint angular velocity because of the known torque-angular velocity relationship of muscle. The implications of this will be discussed in the section concerned with the optimal throw.

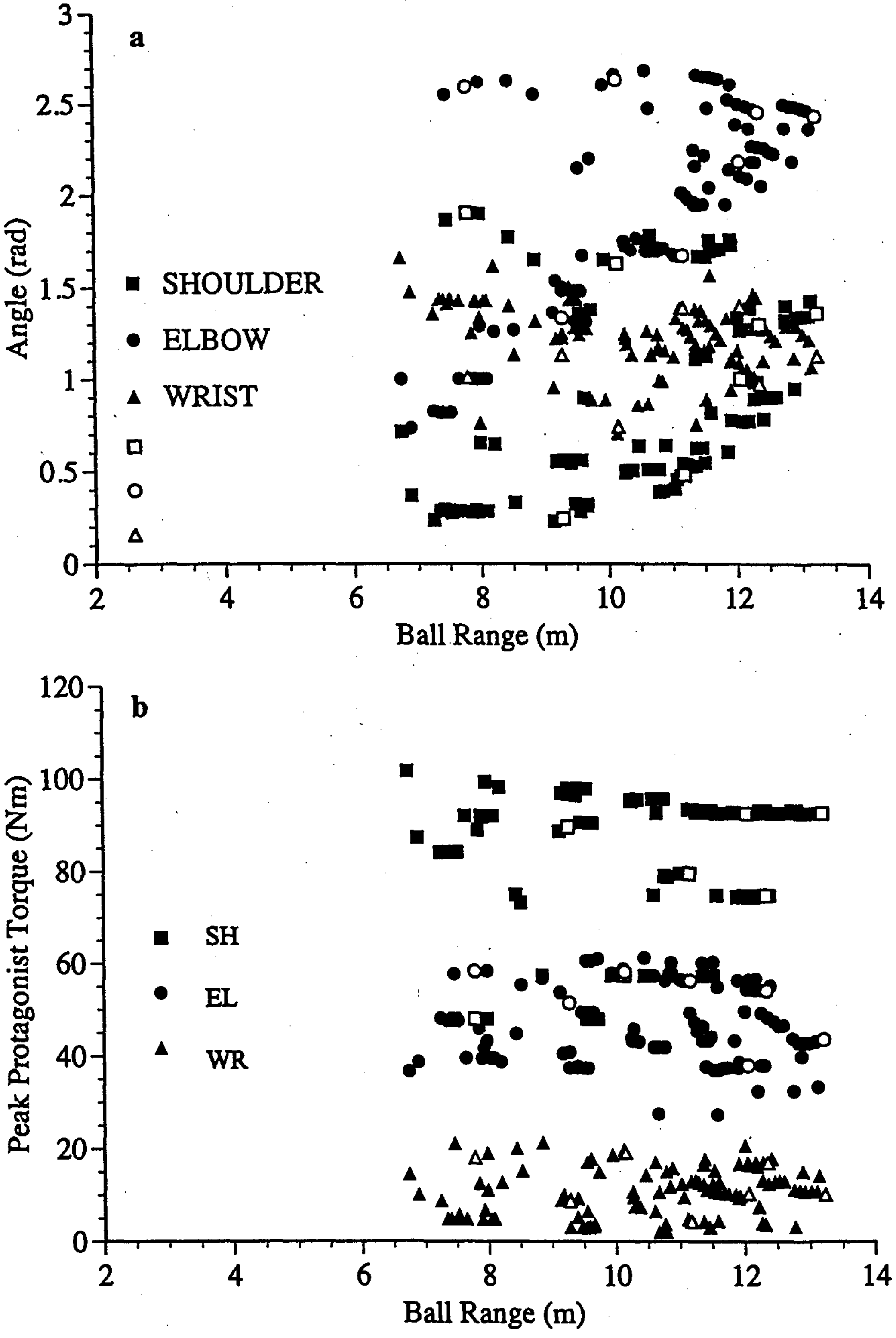


Figure R1-3. a) Joint range of motion vs ball range in 123 sub-maximal throws. b) Peak agonist torque at the shoulder (SH), elbow (EL) and wrist (WR) vs ball range in 123 sub-maximal throws. Significance of open symbols is explained in the text.

Power:

The results from successful throws indicated that high energy in the hand segment was desirable for maximizing performance. In order to determine how energy was transferred distally, muscle moment and joint force power were calculated at the elbow and wrist joints during each throw (Winter, 1989 and Appendix B). In order to be able to compare throws, a single identifying parameter was desirable. The peak power in each throw was determined and plotted against ball range (Figure R1-4). In all throws, there is a greater rate of energy transfer through muscle moment power at the elbow rather than through joint force power (Figure R1-4a). At the wrist, there was generally a greater rate of energy transfer through joint force power rather than through muscle moment power (Figure R1-4b).

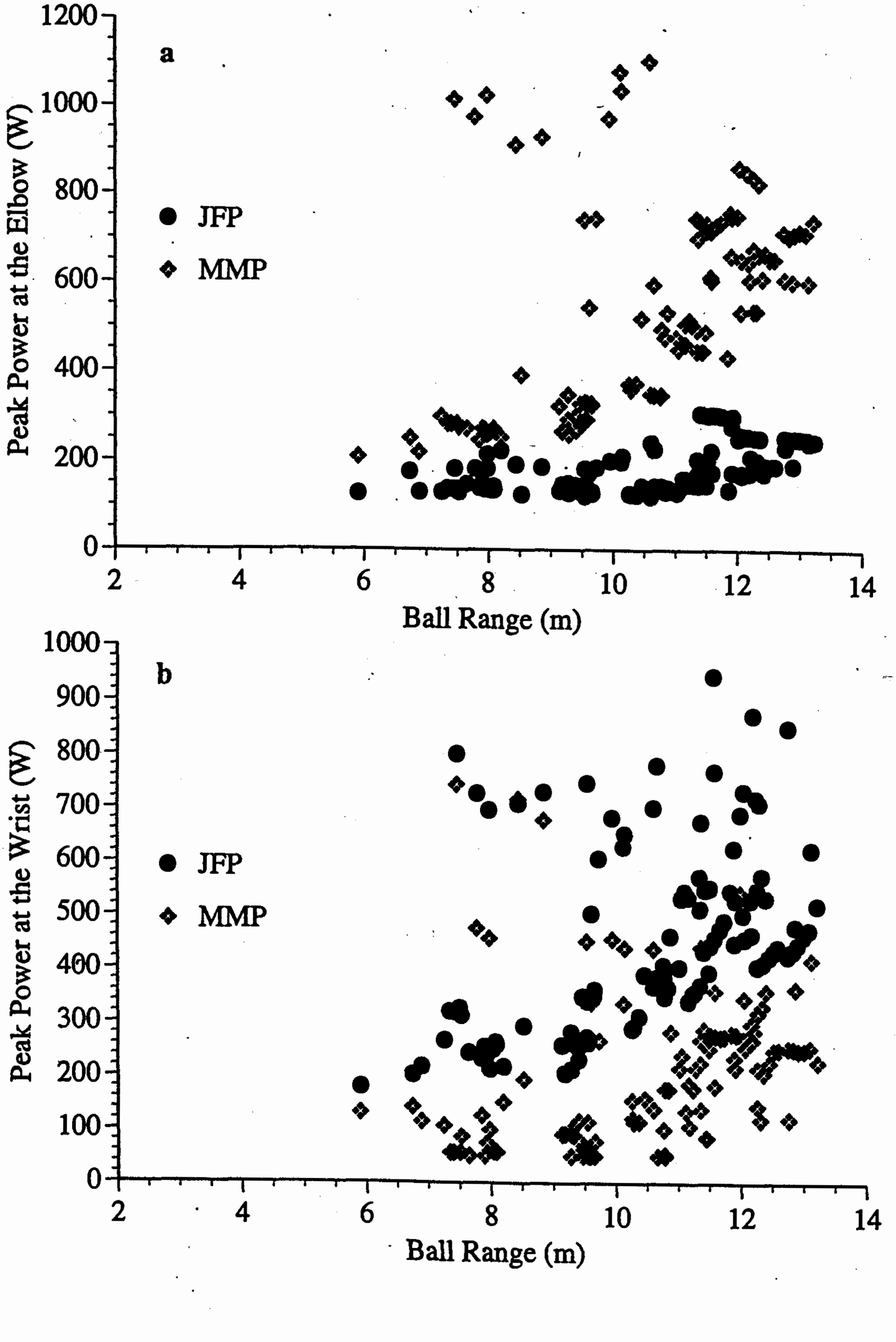


Figure R1-4. Peak muscle moment power (MMP) and peak joint force power (JFP) at the elbow (a) and at the wrist (b) vs ball range in 123 sub-maximal throws.

II. Optimal Throw

Timing and Kinematics:

In the optimal throw, the ball of mass 0.18 kg was projected a distance of 14.778m from the point of release in the hand. The ball left the hand 0.409s after the throw was initiated, with a velocity of 11.21 m.s^{-1} at an angle of 37.4 degrees to the horizontal. The antagonistic muscles at the shoulder, elbow and wrist were activated at the beginning of the throw to induce backswing conditions. After some delay, the antagonists were deactivated and the agonists were activated. The times for onset and offset of each muscle are shown below (Table R1-2).

Table R1-2. Times of initiation of activation and deactivation of the three agonists and three antagonists in the optimal throw.

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.200	0.280	0.270	0.000	0.000	0.050
DEACT:	------	------	------	0.100	0.225	0.250

The agonistic muscle actuators were not activated in a proximal to distal sequence in the optimal throw. Shoulder extensor activity was initiated quite late which allowed considerable backswing of the upper arm prior to its forward motion in the direction of the throw. The delay between the onset of the shoulder and the elbow extensors was 80ms. This delay also allowed negative angular velocity of the forearm relative to that of the upper arm prior to forearm motion in the direction of the throw. The wrist flexor was activated 10ms prior to the elbow extensor. Later onset of the wrist flexor did not bring about any improvement in ball range.

Each of the agonists were activated after their respective antagonists had begun the deactivation process. The delay in time between the initiation of antagonist deactivation and agonist activation was greatest at the shoulder and least at the wrist (0.100s compared to 0.020s). As a result, there was minimal co-contraction between muscles on opposing sides of a joint at the shoulder and the elbow, and more co-contraction at the wrist. Once an agonist was activated it remained fully activated for the duration of the throw. Even though the agonists were not activated in a proximal to distal sequence, the torques produced by these muscles did peak proximally to distally. The times of occurrence of peak torque at the shoulder, elbow and wrist were 0.246, 0.318 and 0.322s, respectively.

The torque and angular velocity profiles for the optimal throw are shown in Figure R1-5. Although the peak torques occurred in a proximal to distal sequence, the peak joint angular velocities did not. At the time of release, the elbow angular velocity continued to increase; whereas, that of the wrist had already peaked.

The criteria for achieving a successful throw are a maximal velocity of the ball in an optimal direction at the time of release. Because the wrist angular velocity at release was low, the question arose as to how the necessarily high release velocity of the ball was obtained. Figure R1-6 illustrates the absolute segmental angular velocity profiles. Segmental angular velocity is defined as the angular velocity of a segment with respect to a global frame of reference, rather than being with respect to the segment more proximal to it. Like the joint angular velocities, a proximal to distal sequencing of peak segmental velocities did not occur. However, the segmental velocity of the hand was greater than that of the forearm at the time of release, providing a high velocity for the ball. In addition, the resultant linear endpoint velocities indicate high velocities of the ball and fingertip at the time of release (Figure R1-7). Both of these velocities continued to increase after release.

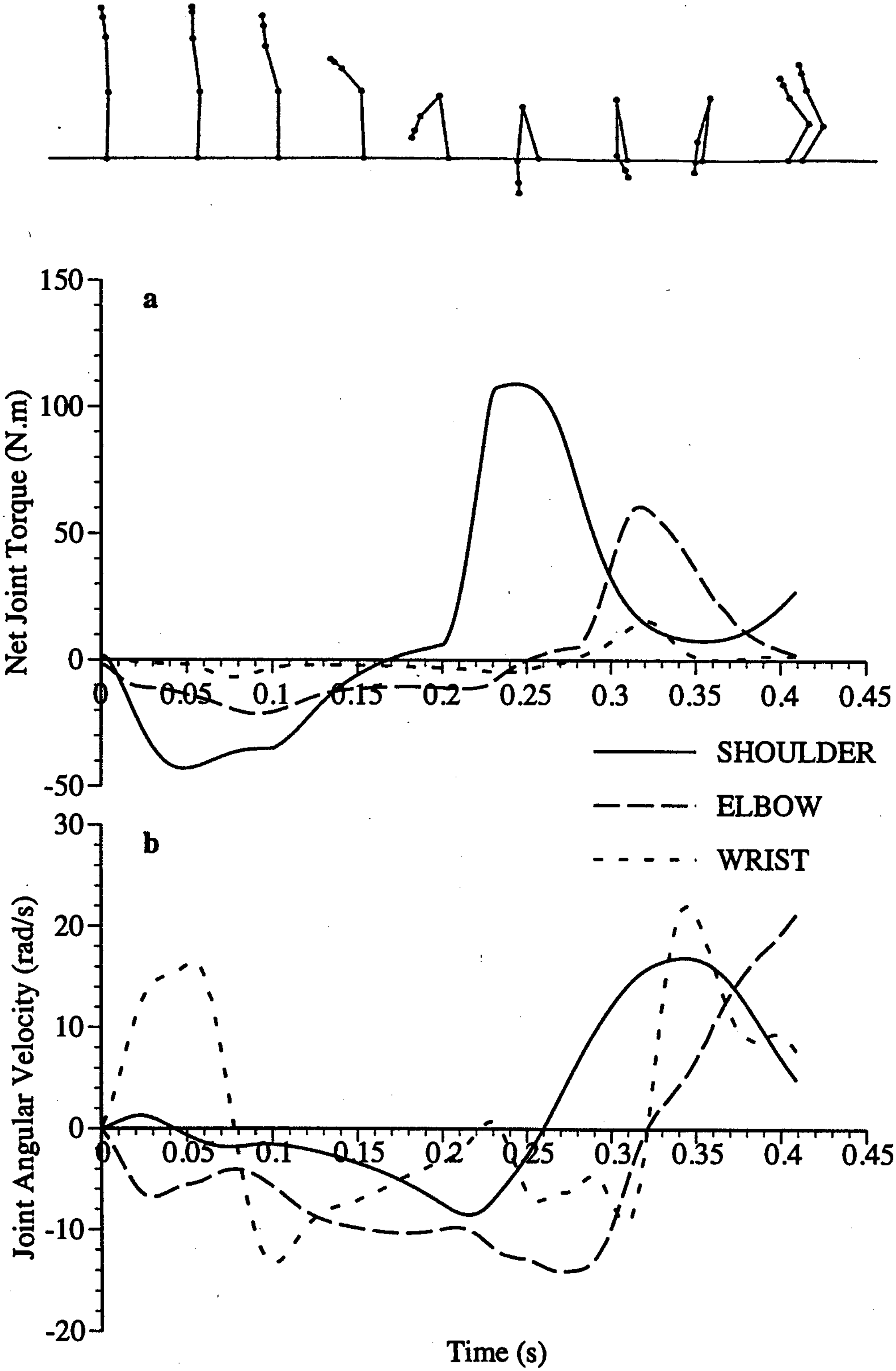


Figure R1-5. Net joint torque profiles (a) and joint angular velocity profiles (b) at the shoulder, elbow and wrist during the optimal throw. Ball release occurred at 0.409s.

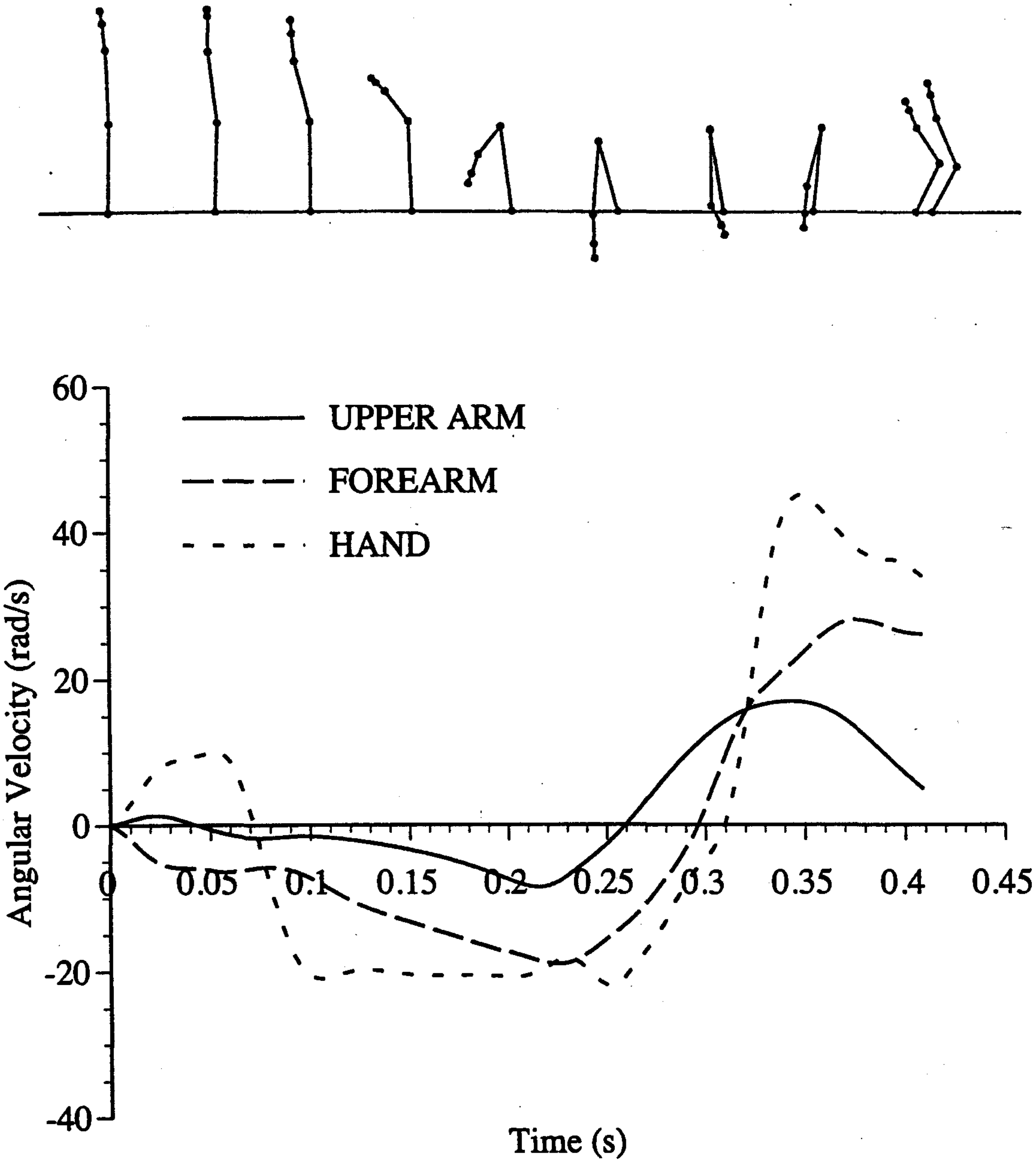


Figure R1-6. Segmental angular velocity profiles during the optimal throw. Ball release occurred at 0.409s.

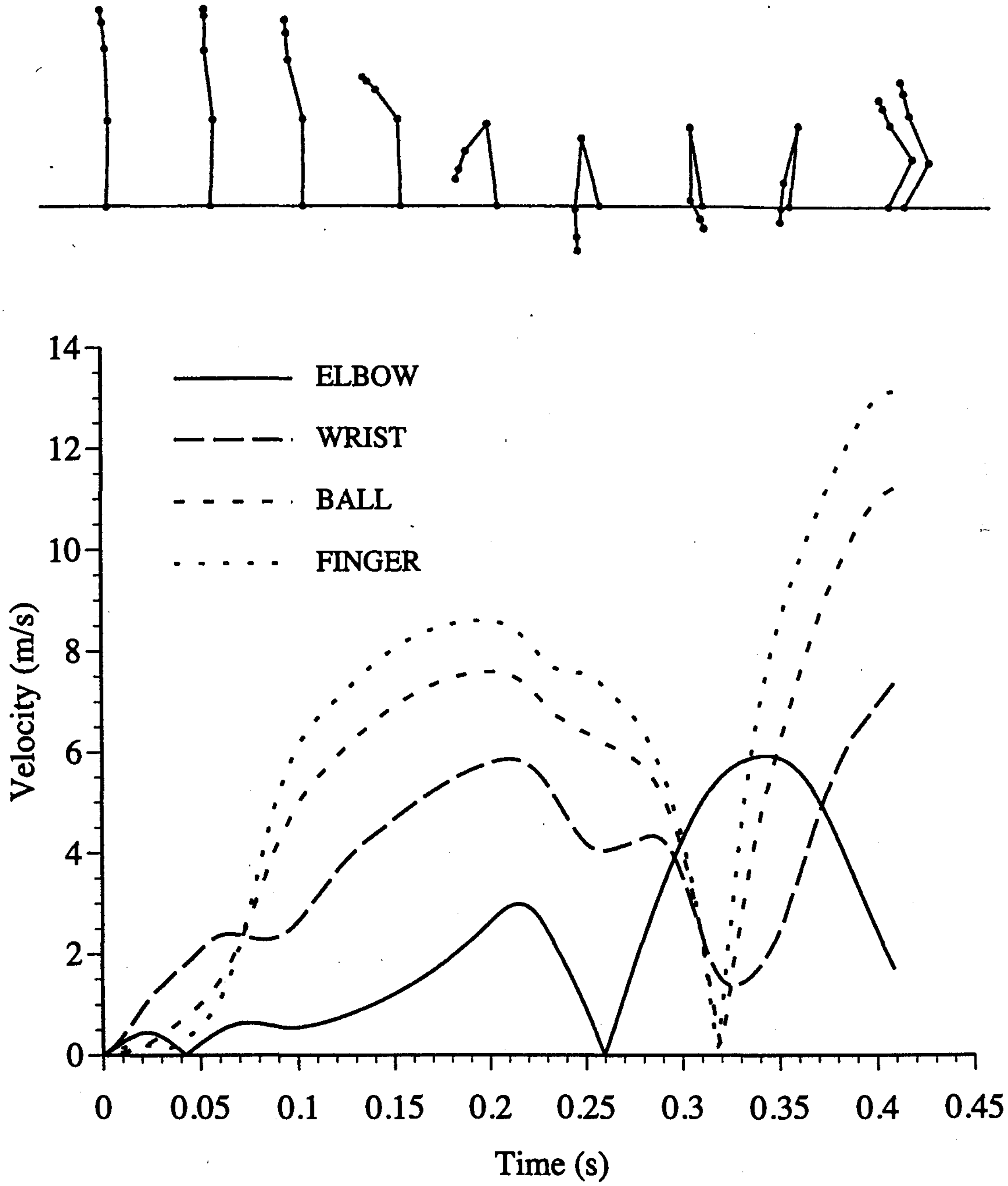


Figure R1-7. Resultant linear endpoint velocities during the optimal throw. Ball release occurred at 0.409s.

Work and Energy:

Evidence for the necessity of a high linear velocity of the hand for the achievement of optimal perfomance is also provided by the segmental energy profiles (Figure R1-8). The rapid rise in total hand energy prior to release is primarily attributed to the translational kinetic energy component, rather than to rotational kinetic or potential energy. The work done by each of the agonistic muscles during the throw is shown in Figure R1-9. At each joint, there was a pattern of negative work, followed by positive work. The negative work was responsible for arresting the backward motion of the backswing. Subsequently, each muscle was able to do positive work. The times of reversal between negative and postitive work did not occur in a proximal to distal sequence. Positive work was firstly developed at the shoulder, followed by a simultaneous development of positive work at the elbow and wrist.

The results concerning the work done during the group of sub-maximal throws in the previous section indicated the importance of favourable torque producing conditions for the muscles as well as having each joint rotate through an appropriate range of motion. In the best throw, the timing of antagonists and agonists allowed a long period of backswing at all joints. This is in comparison to the least successful throws in which the antagonists were active for a short duration and the agonists were activated early in the throw. Figure R1-10 presents the results from a poor throw, with a projected ball range of 10.3m (compared to 14.8m in the best throw). The activation times of the antagonists were the same as those in the best throw, but the onset times of the agonists were 0.150, 0.200 and 0.220 at the shoulder, elbow and wrist, respectively. As a result of the earlier onset of the shoulder and elbow agonists, there was reduced backward rotation of the segments and the muscles were unable to take advantage of the enhanced torques that result from the stretch-shortening cycle (Figures R1-10a and R1-10b compared to Figures R1-5a and R1-5b). Due to the reduced torques during the initial forward phase of the poor throws, the angular accelerations were reduced and joint angular velocities were less than in the best throw. One potential advantage of this is that the muscles will operate on a more favourable region of the torque-angular velocity relationship and continue to generate relatively high torques; however, this benefit does not compensate for the reduced impulse applied early in the throw. The total positive work done by the shoulder and elbow agonists in the poor throw was 31.5 and 17.3 J (compared to 39.7 and 17.7 J during the best throw). The reduced work done by the shoulder in the poor throw is accounted for by both the reduced torque and joint range of motion because of the minimal backswing during the throw.

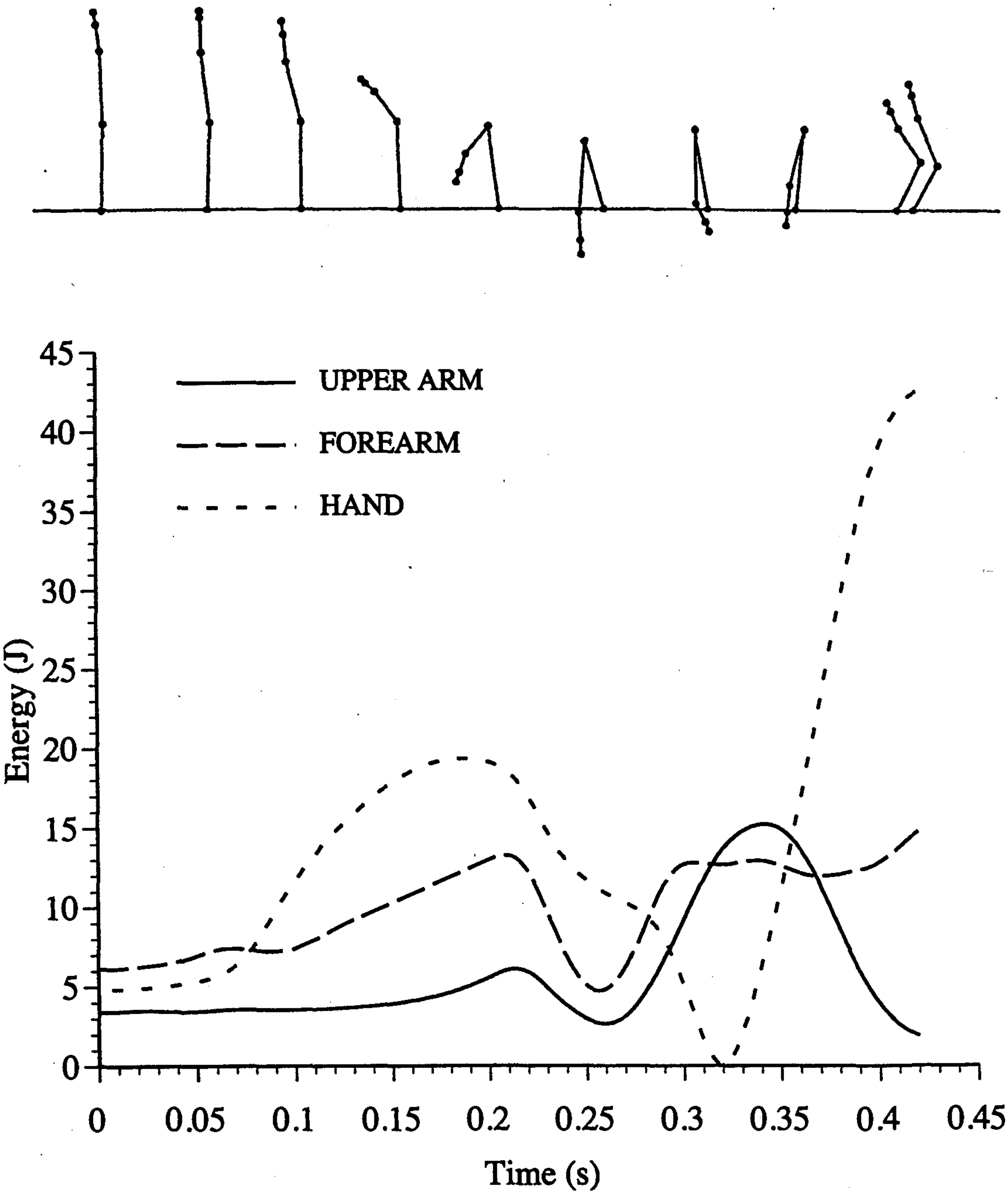


Figure R1-8. Total energy of all segments during the optimal throw. Ball release occurred at 0.409s.

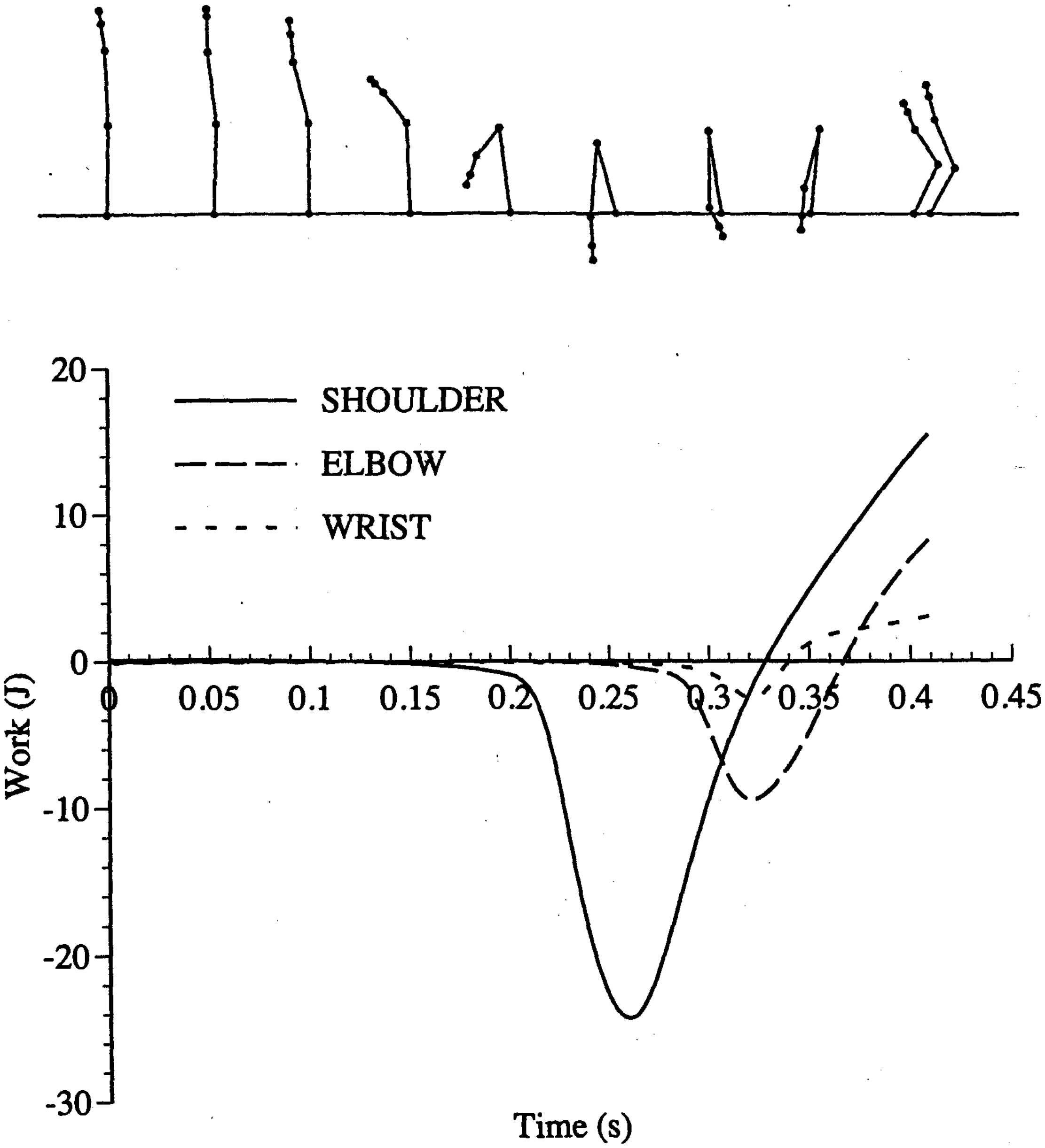


Figure R1-9. Work done by agonist muscles during the optimal throw. Ball release occurred at 0.409s.

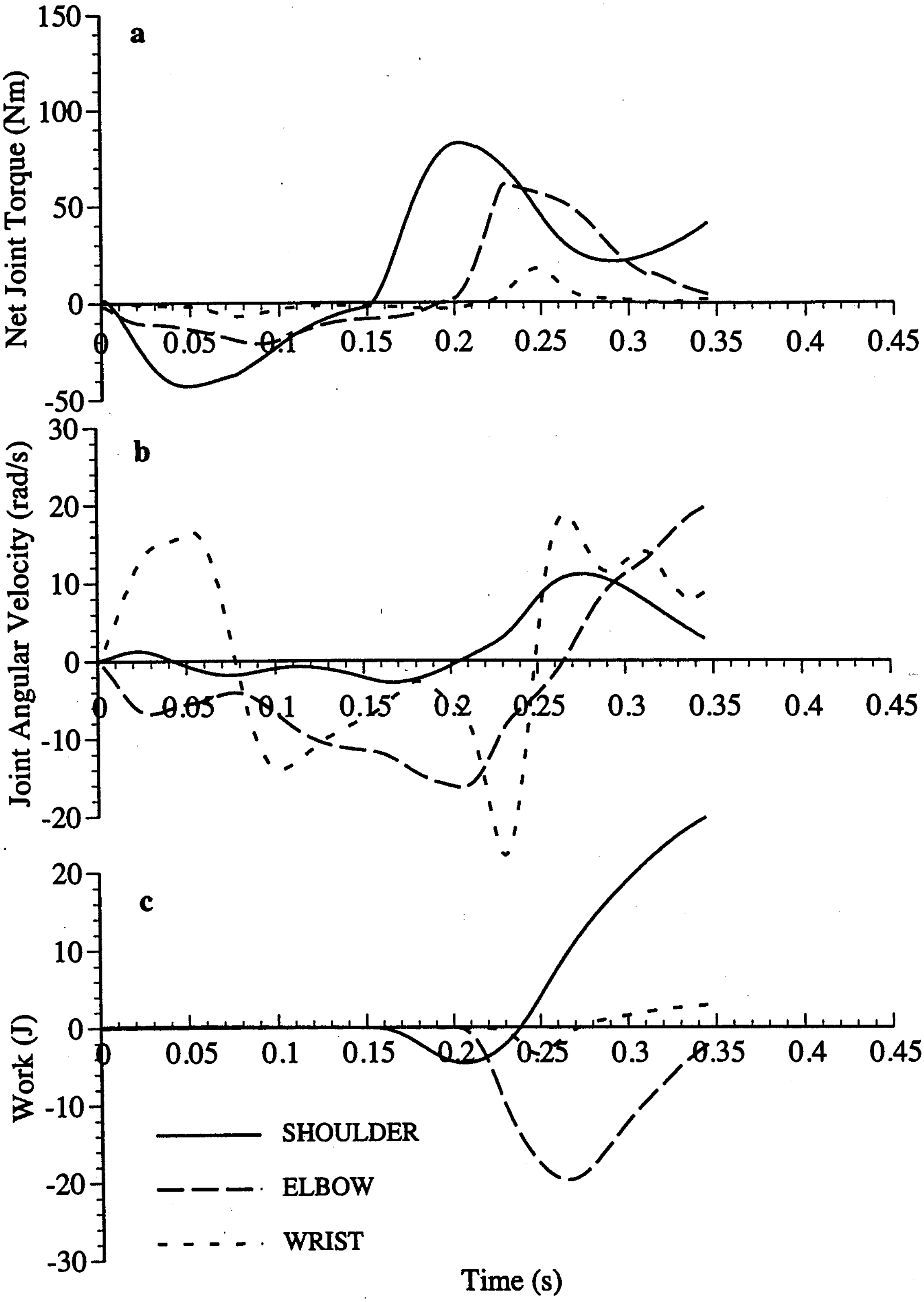


Figure R1-10. (a) Net joint torque profiles, (b) joint angular velocity profiles and (c) work done at the shoulder, elbow and wrist during a sub-maximal throw.

Power:

The power profiles at the elbow joint (Figure R1-11a) indicate a rapid gain in energy of the forearm through the contribution of both the elbow extensor moment and the joint forces at the elbow. The hand segment also underwent a gain in energy prior to ball release. This was due primarily to passive transfer by the joint forces, rather than to the wrist flexor moment (Figure R1-11b).

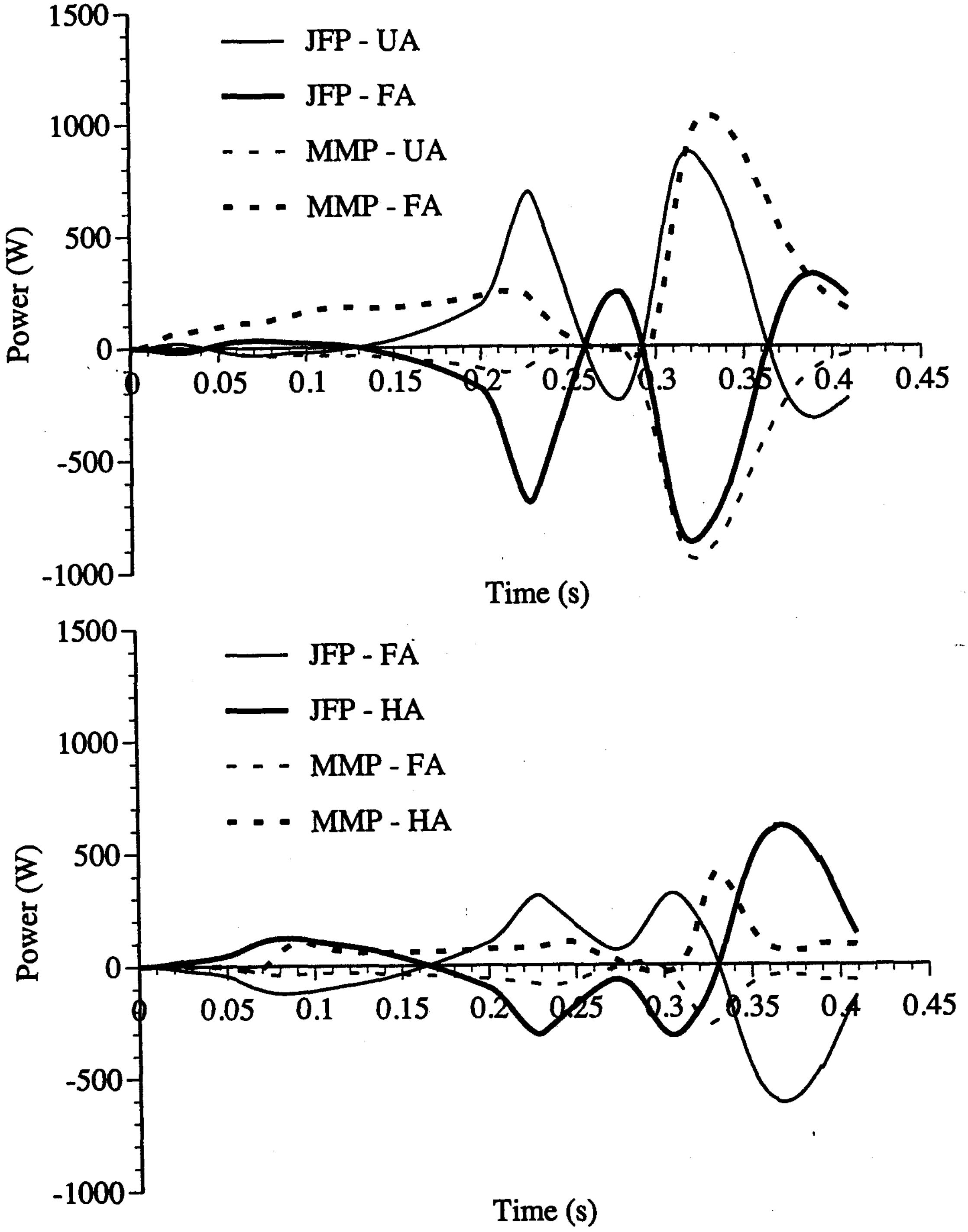


Figure R1-11. (a) Joint force power (JFP) and muscle moment power (MMP) at the elbow during the optimal throw. Bold lines indicate rate of change of energy of the most distal segment (forearm). (b) Joint force power (JFP) and muscle moment power (MMP) at the wrist during the optimal throw. Bold lines indicate rate of change of energy of the most distal segment (hand). Ball release occurred at 0.409s.

DISCUSSION 1

OBSERVATIONS BASED ON SUB-OPTIMAL PERFORMANCE

In throwing, maximal performance, as defined by maximal projected range of the ball from the hand, is achieved by optimizing the times of activation and deactivation of all muscles. One of the primary objectives in trying to maximize performance in throwing is to maximize the energy in the most distal segment during the time before ball release. The importance of this was illustrated in the relationship between ball range and the increase in hand energy shown in Figure R1-1. The contribution of the work done by the agonists to the observed increase in energy of the hand was examined. The relative contribution to the total work done during successful throws was greatest for the shoulder extensor (approximately 68 percent). The elbow extensor and wrist flexor contributed approximately 26 and 6 percent, respectively. Using onset times which ensure these appropriate relative contributions by each muscle to the total work done appears to be critical to the success of the throw. Without it, a trade-off between the work producing potential of the shoulder and elbow muscles ensues (Figure R1-2), resulting in a decrement in performance.

The relative values of work done by the shoulder and elbow in the optimal throw also indicate that the most suitable amount of work done by the shoulder muscle tends towards its maximum; whereas, the work done by the elbow muscle tends towards its minimum. These data emphasize the importance of having the shoulder muscles do the majority of the total work. In addition, the data indicate that the wrist musculature does little work; therefore, contributing minimally to ball velocity. The influence of modifying the work producing capability of each agonist on performance is addressed in the third section of this thesis.

In the successful throws, the ability of the muscles to generate appropriate levels of work is accounted for by favourable torque generating conditions and the range of motion through which each joint rotates. A large backswing was beneficial for both of these objectives, as it enabled the muscles to take advantage of the stretch-shortening cycle and increased the subsequent joint range of motion in the direction of the throw. One of the limiting factors concerning this benefit is that as a joint reaches the limits of its range of motion, the possibility of injury exists. For example, when the time of onset of the shoulder extensor was delayed beyond 0.200s, the resulting projected range of the ball was greater than in the current best throw; however, the shoulder rotated beyond the acceptable limits which may have resulted in injury.

The question still remains as to how the work done by the muscles crossing each joint manifests itself as an increase of energy in the most distal segment. Because the proximal end of the system is fixed at the shoulder joint, momentum can be added to the system only through development of torque at the shoulder. Muscle moments acting at the elbow and wrist have equal and opposite effects on the segments to which the muscles are attached and therefore cannot add momentum to the system as a whole. However, energy can be transferred between segments either through generation of muscle torque or by passive transfer through the action of joint forces. In successful throws, the timing and magnitude of muscle torques must be ideal to allow optimal energy transfer between segments.

OBSERVATIONS BASED ON OPTIMAL PERFORMANCE

The single best throw which projected the ball a maximal distance provides evidence in support of the general statements made in the previous section. Firstly, the hand segment demonstrated a rapid increase in energy during the 90 ms prior to ball release. This increase in energy of the hand is due to a number of contributing factors. In examining the power profiles at the elbow and at the wrist, it is evident that the energy in the system is transferred distally through the action of joint forces and muscle moments. The muscle moment at the elbow is largely responsible for the gain in energy of the forearm; whereas, at the wrist, energy is transferred primarily by the joint forces acting at this joint. The gain of energy of the hand segment due to the wrist flexor moment is short-lived. This is because the torque producing capability of the wrist flexor is largely dependent upon the joint angular velocity at the wrist. After being activated, the increase in torque resulted in increased acceleration of wrist flexion, which in turn had an adverse influence on the ability of the wrist flexor to continue to generate torque due to the nature of the force-velocity relationship of muscle contraction. On the other hand, the joint forces which are active at the wrist are a function of all joint angles, velocities and accelerations. Therefore, in order for the joint forces at the wrist to be effective in transferring energy, there must be optimal patterns of segmental motion throughout the system during the throw. This implicates the importance of optimal timing of onset of all muscles for achieving a pattern of motion which best meets these requirements.

Unlike most of the patterns of motion in multisegmental linkages which have been reported in the literature, the kinematic profiles describing the optimal simulated throw did not follow a proximal to distal sequencing of peak values. The peak angular velocity of the hand segment preceded that of the forearm. This sequence occurred even though the maximal values of the three muscle moments did occur in a proximal to distal sequence.

This observation emphasizes the need for a thorough mechanical analysis when studying multisegmental motion. Assumptions cannot be made regarding cause and effect.

The absence of a proximal to distal sequencing in the kinematic profiles was surprising. Previously, in a three-segment model of overarm throwing, the proximal to distal sequencing of peak joint angular velocities was a robust characteristic of all successful throws (Herring, 1989). However, in the model which Herring used, muscular torques were constant rather than length and velocity dependent. The results from this thesis indicate that the system was forced to alter its behaviour in order to account for the added complexity introduced by the influence of the mechanical properties of muscle. This is in support of Partridge (1979) who stated that "since effective motor control is accomplished, it would appear that the nervous system has the capability of dealing with the problem", p205. The problem that the nervous system is faced with is that "the local rules with which the nervous system must deal in determining motor action vary considerably with the conditions under which the muscles are acting," (Partridge, 1979, p205).

The current results are also not in agreement with the majority of experimental results which have repeatedly demonstrated proximal to distal sequencing of segmental motion. One possible explanation for the lack of agreement is that in those studies in which complete kinetic analyses were carried out, the segmental linkage consisted of only two segments (Feltner, 1989; Putnam, 1993). Although Putnam's work is concerned with kicking rather than throwing, the potential for comparison is greater than with Feltner's pitching study because the kicking movement was planar rather than three-dimensional. If the most distal segment in the current model of throwing were to be removed, then the results would be likely to agree more closely with those of Putnam (1993). It is not possible to postulate how the behaviour of the kicking limb would behave if the influence of the dynamics of the foot segment were to be considered, although, the motion of the shank would likely be affected.

Inspection of Figure R1-5 shows that the temporal pattern of the shoulder and elbow peak joint angular velocities is proximal to distal, but that of the wrist peaks prior to the elbow. Because the criteria of a successful throw include an optimal configuration of the limb at the time of ball release and an optimally directed velocity vector of the ball, it is possible that one role of the motion at the wrist is to fine-tune the orientation of the hand to get a good release angle in order that throwing performance is maximized.

The mechanical properties of muscle are also implicated in the pattern of motion observed in the optimal throw. All three muscles exhibited work profiles in which there was a negative phase, followed by a period of positive work which continued until the completion of the throw. These results indicate that a backswing was used at all joints. The potential benefit of a backswing is twofold. Firstly, by having a segment initially rotate in the backward direction, it allows a greater range of movement during the subsequent motion in the forward direction. The implication of this is that more work can be done by muscles rotating through greater excursions. Secondly, the backswing enables the muscles to take advantage of the force enhancement which occurs during the stretch-shortening cycle. The results in Figure R1-5 illustrate that the magnitude of each torque is large at the point in time when joint angular velocity becomes positive. Were there no backswing, then the muscles would be in a situation where torque must be developed from rest. In this case, the peak torque and impulse provided by that muscle would be less. To illustrate the difference in performance between throws with and without initial backswing, a throw was simulated in which the starting position was that of the backward-most position during the optimal throw. Activation of all muscles began at zero time in order to reduce the possibility of occurrence of stretch-shortening contractions. The decrement in torque production and joint angular velocity is shown in Figure D1-2 (compare with Figure R1-5). With no backswing, the projected range of the ball decreased to 10.5 m from 14.8 m in the optimal throw.

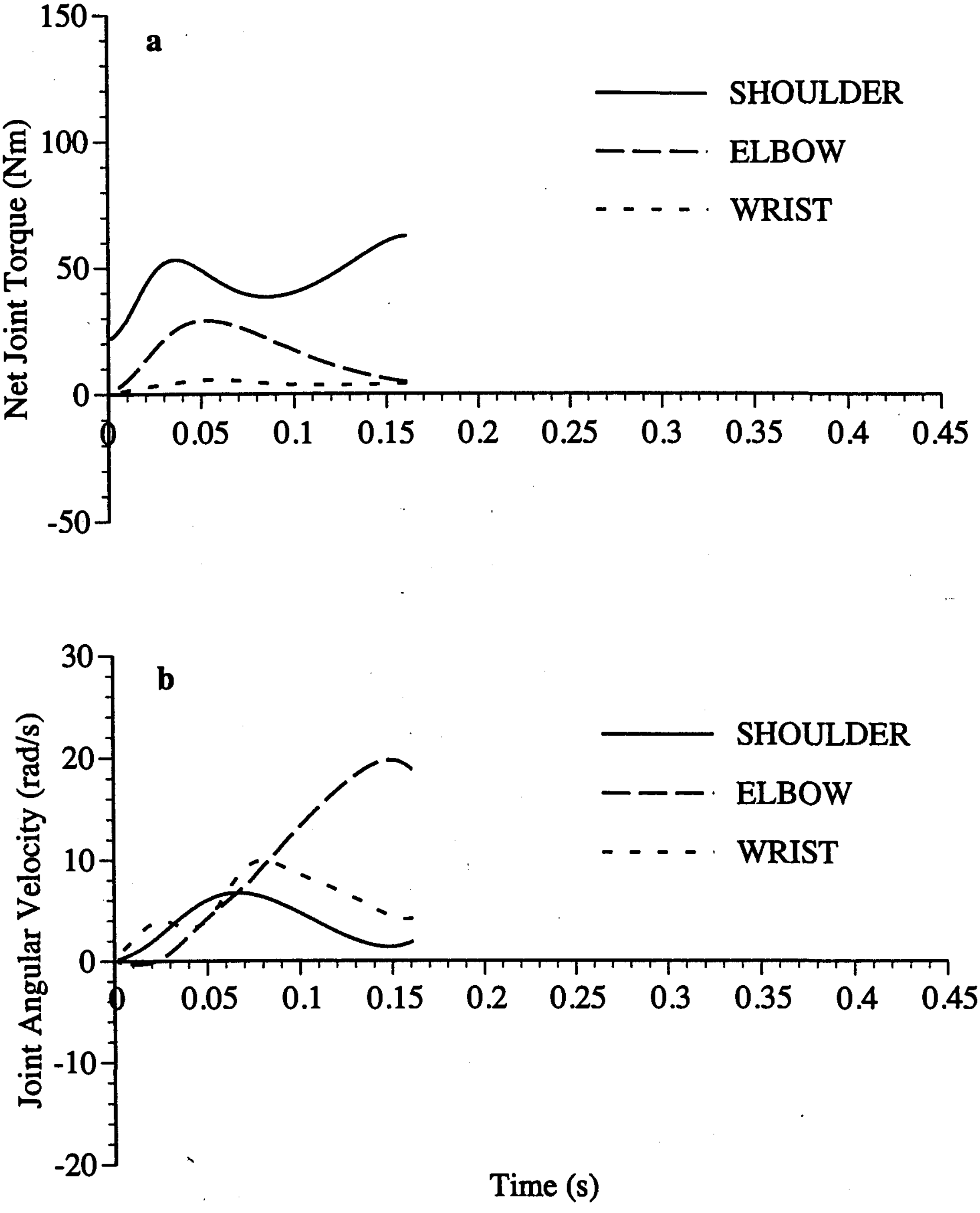


Figure D1-1. Net joint torque profiles (a) and joint angular velocity profiles (b) at the shoulder, elbow and wrist during a throw in which there was no backswing. Ball release occurred at 0.156s.

Chapter 4. Proximal Antagonism

METHODS 2

1. Optimal Throw

In an effort to improve the performance of the original optimal throw, the influence of inducing a shoulder flexor torque late in the throw was investigated. To do so, the shoulder antagonist was activated at different times near the end of the throw. This active decrease and reversal of the proximal torque was thought to be a means of enhancing transfer of momentum from the proximal to distal segments (Robertson and Mosher, 1985), and has previously proven successful in increasing simulated throwing performance (Herring, 1989). Deactivation of the shoulder agonist was also required in order to minimize the amount of shoulder cocontraction. The time of ball release in the optimal throw from the previous section was 0.409s. The times at which shoulder extensor deactivation and shoulder flexor activation were initiated are shown in Table M2-1. In each of these simulated throws, the times of onset and duration of the remaining muscles were the same as those which generated the previous best throw:

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.200	0.280	0.270	0.000	0.000	0.050
DEACT:	------	------	------	0.100	0.225	0.250

Table M2-1. Times of onset (s) of shoulder flexor activation and shoulder extensor deactivation used to modify the optimal throw.

SHOULDER FLEXOR ACTIVATION	SHOULDER EXTENSOR DEACTIVATION
0.375	0.350
0.375	0.375
0.375	0.400
0.380	0.380
0.380	0.390
0.380	0.400
0.385	0.375
0.385	0.380
0.385	0.385
0.400	0.375
0.400	0.385
0.400	0.400

2. *Sub-optimal Throws*

The effect of proximal torque reversal on a sub-optimal throw was also investigated. This throw was generated using times of agonist onset from a different region of the original global search field from that which produced the optimal throw. The primary difference between the sub-optimal throw generated in this section and the optimal throw from the previous section was the early onset time of the shoulder agonist (i.e. 0.050s compared to 0.200s). These onset times were selected because of the resulting difference in the orientation of the arm at the time of ball release. The times of onset of the sub-optimal throw without proximal antagonism were:

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.050	0.125	0.170	0.000	0.000	0.000
DEACT:	------	------	------	0.100	0.100	0.100

The strategy used to determine the effect of proximal antagonism on this sub-optimal throw was similar to that which was used to modify the optimal throw in the previous section. A large number of possible combinations of agonistic deactivation and antagonistic activation times were used to simulate a batch of 54 throws. The times used to generate these throws are given in Table M2-2.

Table M2-2. Times of onset of shoulder flexor activation and shoulder extensor deactivation used to modify the sub-optimal throw.

SHOULDER FLEXOR ACTIVATION (s)	SHOULDER EXTENSOR DEACTIVATION (s)
0.225	0.100
0.230	0.125
0.235	0.150
0.240	0.175
0.245	0.200
0.250	0.225
	0.250
	0.275
	0.300

The activation and deactivation times which produced the throw in which ball range was maximized were identified. This maximum range throw was selected for further analysis in the following chapter.

RESULTS 2

A. *Optimal Throw*

The onset of proximal antagonism prior to ball release did not enhance performance of the optimal throw in terms of the projected range of the ball. In fact, the influence of proximal antagonism was detrimental to throwing performance. The detrimental effects were greatest with earlier deactivation of the agonist and earlier activation of the antagonist. The times of shoulder extensor deactivation and shoulder flexor activation and the resulting ball range are given in Table R2-1.

Table R2-1. Modified times of onset of shoulder muscle activation and the influence on ball range.

	SHOULDER FLEXOR ACTIVATION (s)	SHOULDER EXTENSOR DEACTIVATION (s)	BALL RANGE (m)
	0.375	0.350	11.612
	0.375	0.375	12.562
	0.375	0.400	12.872
	0.380	0.380	13.598
	0.380	0.390	13.733
	0.380	0.400	13.775
	0.385	0.375	14.010
	0.385	0.380	14.174
	0.385	0.385	14.253
	0.400	0.375	14.511
	0.400	0.385	14.693
	0.400	0.400	14.775
OPTIMAL:			**14.778**

One of these throws was selected for further analysis in order to explain the mechanisms which underlie the decrement in throwing performance that occurs with proximal antagonism. The throw in which activation of the antagonist occurred at 0.385s and deactivation of the agonist was at 0.375s was chosen because the behaviour of the system was representative of the others. In this throw, the ball left the hand at the same time as in the optimal throw (0.409s) but was projected only 14.010m. The velocity of release decreased from 11.21 $m.s^{-1}$ to 10.85 $m.s^{-1}$ with proximal antagonism, and the angle of ball release was adjusted from 37.38 to 42.20 degrees to the horizontal. The orientation of the segments at the instant of ball release is shown in Figure R2-1. The coordinates of the centres of mass of all segments indicate that with proximal antagonism, the segments were moved in the backward and upward direction, compared to the throw without antagonism (Table R2-2).

The torque and joint angular velocity profiles of the optimal throw are superimposed on those of the throw with proximal antagonism in Figure R2-2. The late and rapid decrease in the shoulder torque is readily apparent in Figure R2-2a. This shoulder torque reversal resulted in a reduced joint angular velocity at the shoulder and an enhanced joint angular velocity at the wrist (Figure R2-2b). A comparison of the magnitude of all three joint angular velocities at the time of release is given in Table R2-2. The most notable influence of shoulder antagonism was the greater magnitude of wrist angular velocity (12.5 compared to 7.8 $rad.s^{-1}$).

The segmental angular velocity profiles illustrate the reduced velocity of the upper arm and forearm in the final 0.034s of the throw compared to the optimal throw (Figure R2-3). The angular velocity of the hand was greater in the throw with shoulder antagonism than in the throw without, but as the results indicated, this increase in angular velocity of the hand did not contribute to an increase in ball range. The magnitude of all segmental angular velocities at the time of release are presented in Table R2-2 for comparison.

The detrimental effect of the onset of proximal antagonism was also evident in the resultant endpoint velocity profiles (Figure R2-4). The resultant velocity of the ball at release was 0.4 $m.s^{-1}$ less in the throw with activation of the shoulder flexor than in the throw without. The vertical and horizontal components of the velocity of the centre of mass of each segment are given in Table R2-2. With the onset of shoulder antagonism, the velocity of all segments in the horizontal direction was less than in the throw without antagonism and the velocity of all segments in the vertical direction was greater.

In addition to the kinematic parameters, the energy of all segments in both throws at the time of ball release are compared in Table R2-2. The total segmental energy of all segments is less in the throw with proximal torque reversal. The potential energy of all segments is slightly greater, but the contribution of potential energy to the total is minimal and does not compensate for the much reduced translational kinetic energy of the hand (34.48 J compared to 37.24 J).

Table R2-2. Comparison of kinematic and kinetic parameters at the instant of ball release for the optimal throw and the throw with proximal antagonism.

		OPTIMAL THROW	THROW WITH ANTAGONISM
	UPPER ARM	(0.132, 0.077)	(0.130, 0.080)
CM (X,Y)	FOREARM	(0.203, 0.258)	(0.197, 0.263)
	HAND	(0.017, 0.441)	(0.009, 0.444)
	UPPER ARM	(0.378, -0.645)	(0.162, -0.261)
CM $(\dot{X},\dot{Y})$	FOREARM	(2.990, 1.103)	(2.228, 1.779)
	HAND	(8.358, 6.402)	(7.443, 6.871)
	SHOULDER	4.90	2.01
JOINT ANG VEL	ELBOW	21.24	21.57
	WRIST	7.81	12.50
	UPPER ARM	4.90	2.01
SEG ANG VEL	FOREARM	26.14	23.59
	HAND	33.94	36.08
	UPPER ARM	2.73	1.97
TOTAL SEG ENERGY	FOREARM	13.62	11.68
	HAND	41.02	38.38
	UPPER ARM	0.642	0.108
TOT. KIN. ENERGY	FOREARM	6.663	5.333
	HAND	37.243	34.477
	UPPER ARM	0.350	0.059
ROT. KIN. ENERGY	FOREARM	3.641	2.965
	HAND	0.865	0.977
	UPPER ARM	1.734	1.802
POTENTIAL ENERGY	FOREARM	3.321	3.385
	HAND	2.907	2.927

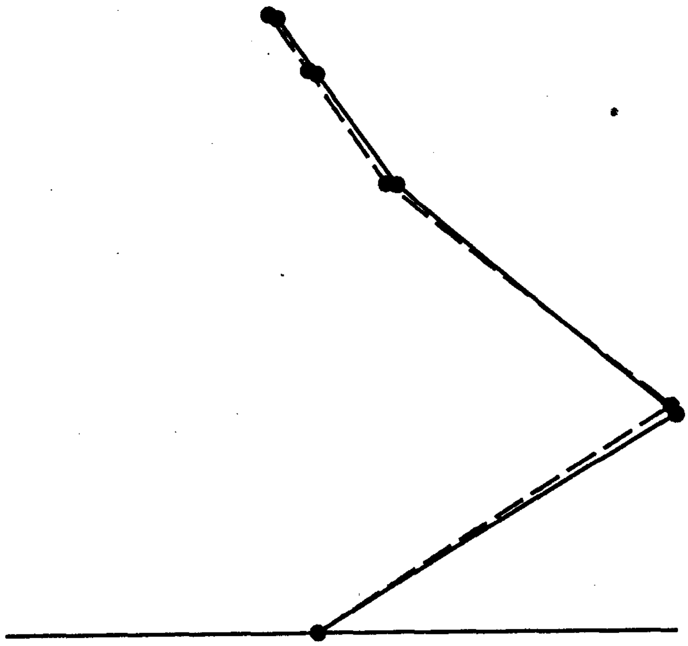


Figure R2-1. The orientation of the segments at the instant of ball release in the optimal throw (solid line) and the throw with shoulder antagonism (dashed line).

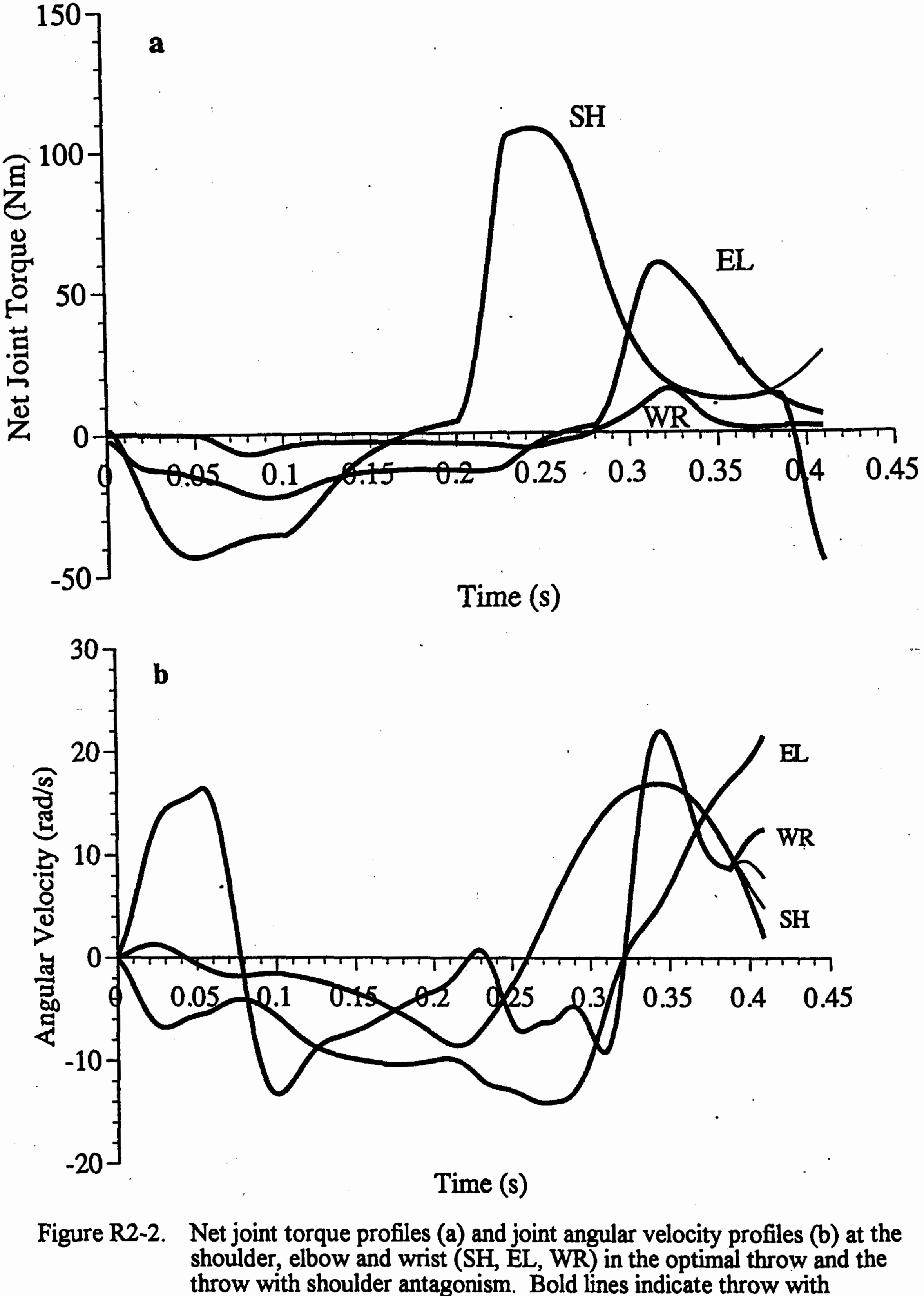


Figure R2-2. Net joint torque profiles (a) and joint angular velocity profiles (b) at the shoulder, elbow and wrist (SH, EL, WR) in the optimal throw and the throw with shoulder antagonism. Bold lines indicate throw with antagonism.

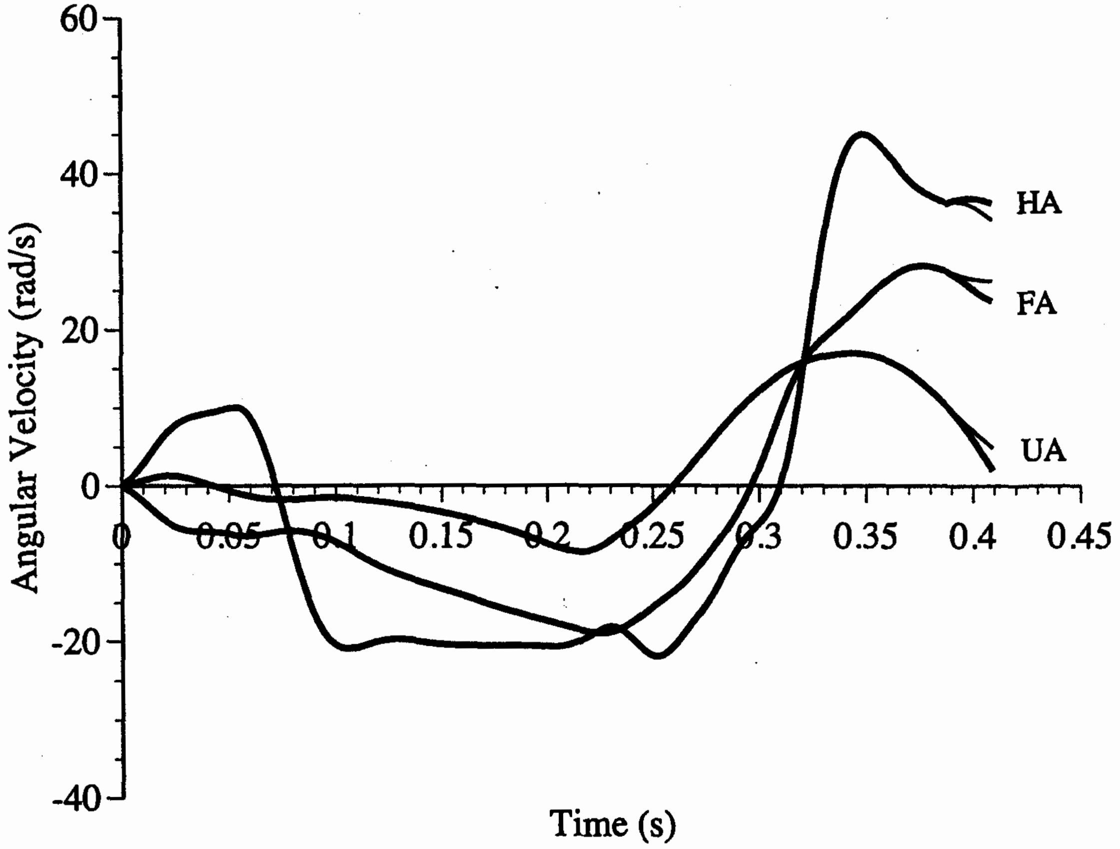


Figure R2-3. Segmental angular velocity profiles of the upper arm (UA), forearm (FA) and hand (HA) in the optimal throw (thin lines) and the throw with shoulder antagonism (bold lines).

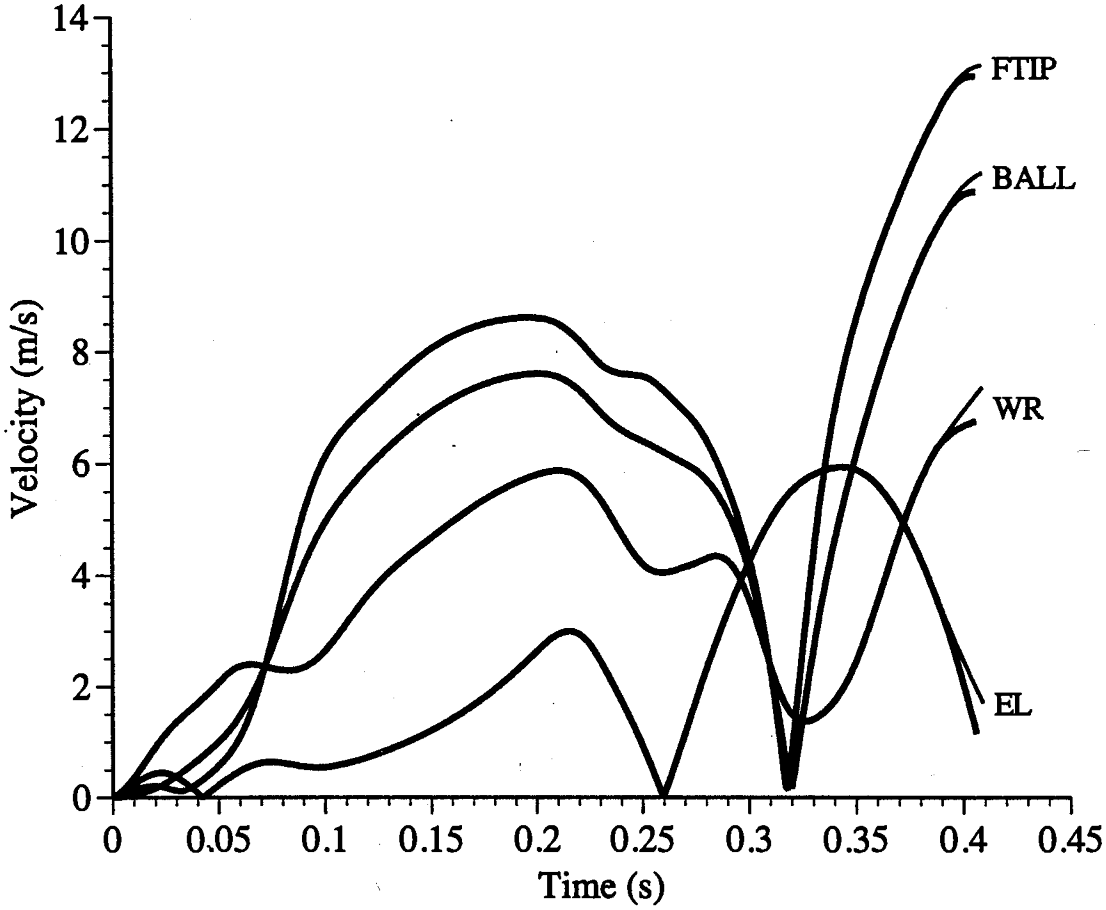


Figure R2-4. Resultant linear endpoint velocity profiles of the elbow (EL), wrist (WR), ball and fingertip (FTIP) in the optimal throw (thin lines) and the throw with shoulder antagonism (bold lines).

B. Sub-Optimal Throw

The distance the ball was projected in the sub-optimal throw without proximal antagonism was 9.330m. The times of onset of activation for this throw are shown below:

	AGONISTS			ANTAGONISTS		
	SH EXT	EL EXT	WR FLEX	SH FLEX	EL FLEX	WR EXT
ACT:	0.050	0.125	0.170	0.000	0.000	0.000
DEACT:	------	------	------	0.100	0.100	0.100

When the shoulder extensor muscle was deactivated at 0.225s and the shoulder flexor was activated at 0.235s, ball range increased to 9.337m. While this is not a significant increase in throwing performance, the difference does show that the strategy of inducing a negative torque at the proximal end of the system may be advantageous. In the throw without antagonism, the ball left the hand with a velocity of 8.669 $m.s^{-1}$ which was nearly identical to the release velocity of the throw without antagonism (8.668 $m.s^{-1}$). The angle of the velocity vector at release was slightly greater in the throw with antagonism (27.10 compared to 27.002 degrees to the horizontal). A second observation regarding these two throws is that ball release occurred 5ms later in the throw with antagonism (0.261s compared to 0.256s).

Inspection of the orientation of the arm segments at the time of ball release indicates that the configuration of the segments differed considerably between these two throws (Figure R2-5). The fact that release occurred later in this throw means that the arm had more time to move in the direction of the throw, giving the coordinates of the ball the advantage of having a greater magnitude in the X- and Y-directions (Table R2-3).

Figure R2-6a illustrates the torque and joint angular velocity profiles associated with the sub-optimal throw with and without shoulder antagonism. The onset of shoulder antagonism resulted in a decrease in shoulder and wrist angular velocities at release compared to the throw without antagonism (Figure R2-6b and Table R2-3). An additional effect, which did not occur when the optimal throw was modified by shoulder antagonism, was an increase in elbow angular velocity (compare Figure R2-2b with Figure R2-6b).

Table R2-3 compares selected kinematic and kinetic variables for the two sub-optimal throws. The most apparent difference between the two throws was increased forearm angular velocity with antagonism (18.94 rad.s^{-1} compared to 16.57 rad.s^{-1} at the time of release); however, this did not manifest itself as an increase in the resultant velocity of the ball or tip of the finger. With shoulder torque reversal, there were several parameters which did change in favour of increasing performance, albeit only slightly. The total energy of the hand was greater with proximal antagonism (26.91J compared to 26.79J). The observed increase in total energy was due to an increase in translational kinetic energy of the hand and greater potential energy of all segments.

Table R2-3. Comparison of kinematic and kinetic parameters at the instant of ball release for a sub-optimal throw and the sub-optimal throw with proximal antagonism.

		SUB-OPTIMAL THROW	SUB-OPT WITH ANTAGONISM
	UPPER ARM	(0.087, 0.125)	(0.085, 0.127)
CM (X,Y)	FOREARM	(0.150, 0.405)	(0.157, 0.414)
	HAND	(0.018, 0.627)	(0.050, 0.649)
	UPPER ARM	(0.307, -0.214)	(-0.126, 0.084)
CM ($\dot{X}$,$\dot{Y}$)	FOREARM	(2.659, 0.331)	(20.032, 0.887)
	HAND	(7.281, 3.503)	(7.261, 3.56)
	SHOULDER	2.46	-0.99
JOINT ANG VEL	ELBOW	14.12	19.93
	WRIST	14.59	10.79
	UPPER ARM	2.46	-0.99
SEG ANG VEL	FOREARM	16.57	18.94
	HAND	31.16	29.73
	UPPER ARM	3.06	2.90
TOTAL SEG ENERGY	FOREARM	11.39	10.46
	HAND	26.79	26.91
	UPPER ARM	0.16	0.03
TOT. KIN. ENERGY	FOREARM	4.71	3.22
	HAND	21.93	21.97
	UPPER ARM	0.09	0.01
ROT. KIN. ENERGY	FOREARM	1.46	1.91
	HAND	0.73	0.66
	UPPER ARM	2.82	2.86
POTENTIAL ENERGY	FOREARM	5.21	5.33
	HAND	4.13	4.28

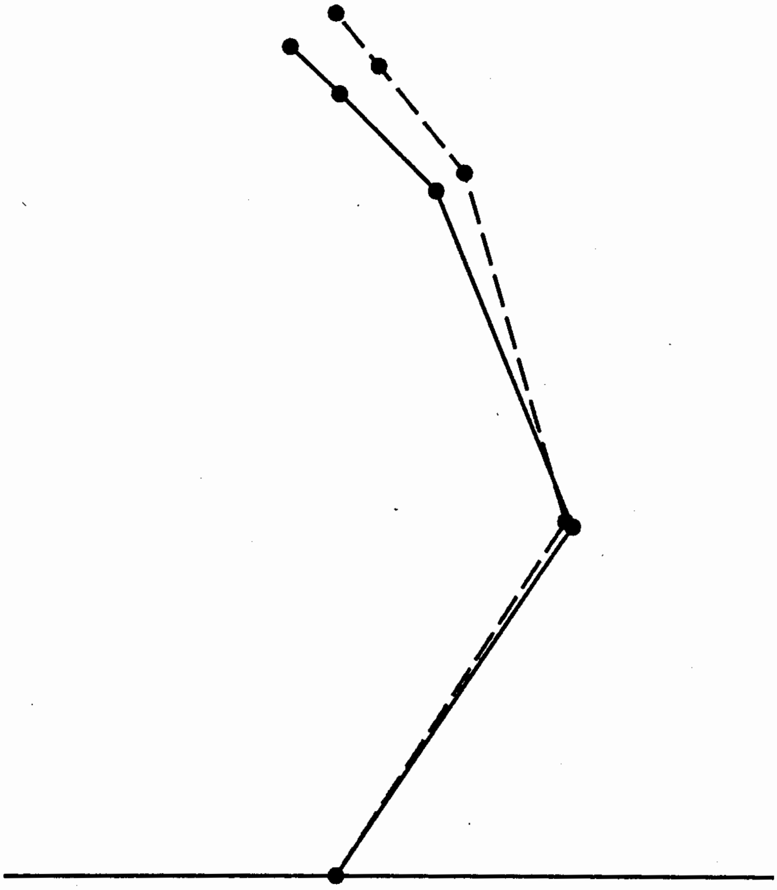


Figure R2-5. The orientation of the segments at the instant of ball release in a sub-optimal throw without shoulder antagonism (solid line) and a throw with shoulder antagonism (dashed line).

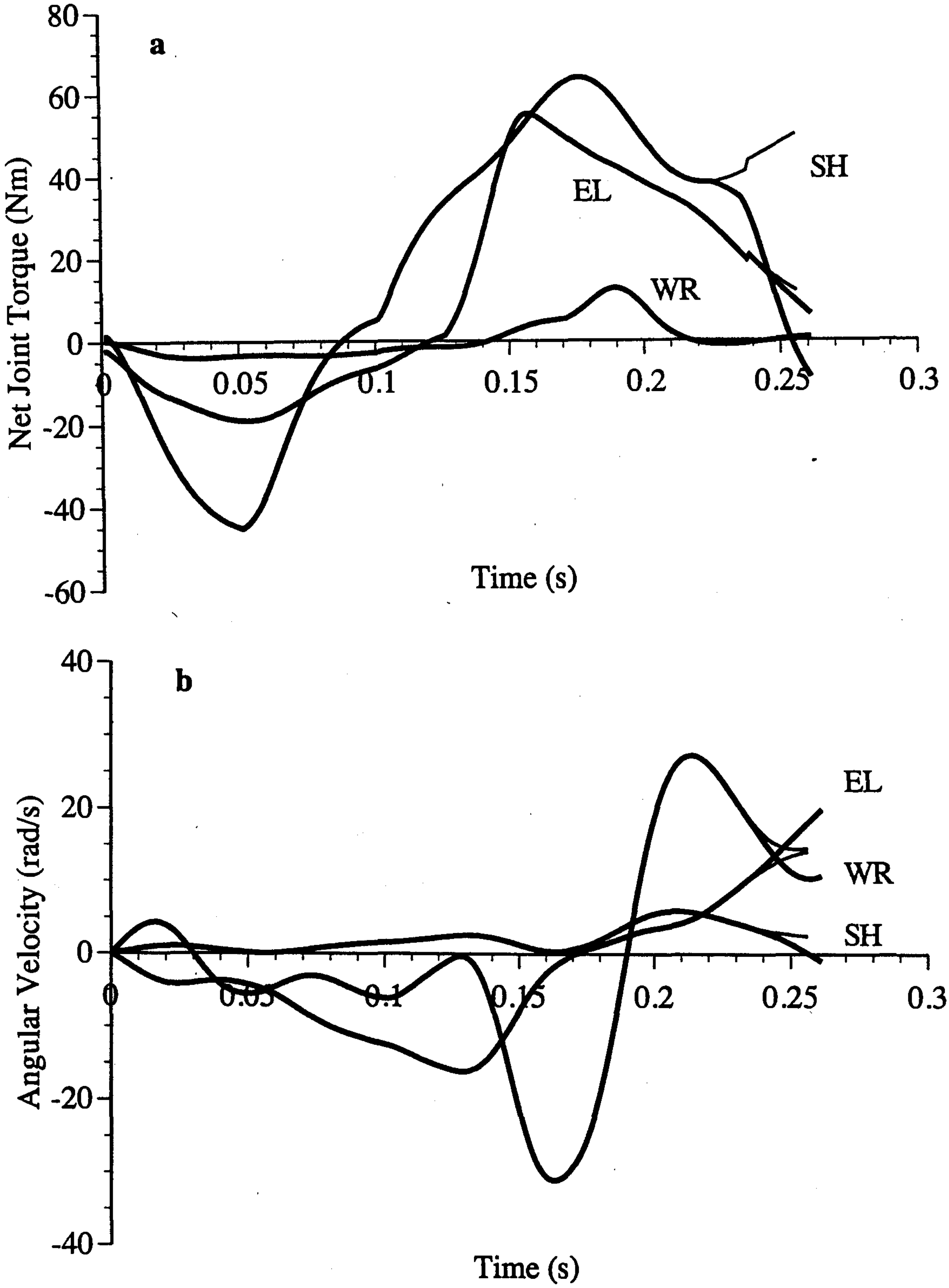


Figure R2-6. Net joint torque profiles and (a) joint angular velocity profiles (b) at the shoulder (SH), elbow (EL) and wrist (WR) in the sub-optimal throw (thin lines) and the sub-optimal throw with shoulder antagonism (bold lines).

DISCUSSION 2

Generally speaking, when an antagonistic torque was developed at the most proximal joint late in simulated overarm throws, there was no increase in the distance the ball was projected from the hand. When the optimal throw was modified by many combinations of times of onset of shoulder antagonist activation and shoulder agonist deactivation, no throw was produced in which the ball was projected farther than it had been in the original optimal throw. A second, non-optimal throw was also modified by the initiation of shoulder antagonism. There were several cases in which performance improved; however, the improvement was minimal (9.337m compared to 9.330m). The objective of the following discussion is to explain why the active generation of an antagonistic torque at the most proximal joint did not improve throwing performance. The findings are presented in light of results from other investigations involving computer simulated multisegmental motion and studies of human motion.

Firstly, the oversimplified explanation by Alexander (1983) that a reduction in the velocity of the more proximal segment by active generation of an antagonistic torque will result in an increase of the velocity of the adjacent, distal segment has been refuted by Phillips et al. (1983). Phillips et al. and Putnam (1993) have emphasized that the configuration and kinematics of the segments must be known before the influence of the segments on each other can be determined. In addition, Putnam (1983) has shown that the angular velocity of the proximal segment in the lower limb decreases in the absence of any antagonistic torque at the hip, and that active deceleration of the thigh may be disadvantageous to the velocity of the shank. The current results support this finding.

There are a number of possible reasons for a decrease in angular velocity of a segment. The assumption cannot be made that activation of an antagonistic muscle at the segments's proximal end is the cause. A second reason for a reduced joint angular velocity is a decrease in agonistic torque because of a reduction in activation of the agonistic muscles. Putnam (1983) also showed in kicking that the decrease in velocity of a segment can be due to the influence of the kinematics of the segment more distal to it. Finally, because the force-producing capabilities of a muscle are partially dependent upon the kinematics of the system, rapid joint angular velocities can put the muscles crossing that joint in an unfavourable region of their force-velocity relationship. As a result, lower forces are produced by the muscles, and the joint angular acceleration decreases.

In the present study, the results from the optimal throw demonstrated that the angular velocity of the upper arm segment decreased in the absence of any antagonistic torque at the shoulder (Figure R2-2b). Further reduction in upper arm angular velocity which occurred in the throw with shoulder antagonism was not advantageous with regard to increasing the velocity of the forearm. This indicates that the theory that an active reduction in the velocity of the most proximal segment induces a transfer of momentum in the proximal to distal direction is not true in all cases, and in fact, that this approach can be detrimental to performance.

The significant influence of the force-velocity relationship of muscle on the behaviour of the system is clearly evident. At the shoulder and elbow, large muscle torques are associated with low joint angular velocities. Subsequently, as the joint angular velocities increased, the magnitudes of the respective joint torques decreased. It appears, then, that the mechanical properties of muscle dictate, to some extent, the behaviour of the segments in trying to achieve optimal performance. Antagonistic torques are not required to bring about the observed reduction in proximal joint angular velocity because reduced velocities occur due to the influence of the force-velocity relationship of muscle.

The results from the four throws which were analysed indicate the importance of using an appropriate kinematic variable when evaluating the success of a particular technique. When an antagonistic torque was developed at the shoulder, there was an increase in wrist angular velocity and in the angular velocity of the hand segment;

however, there was not an increase in the resultant linear endpoint velocity of the wrist, ball or finger tip. Because throwing performance is ultimately determined by the velocity vector of the ball as it leaves the hand, care must be taken to ensure that adjustments are made to technique based on the most appropriate criteria.

The resultant linear endpoint velocities of all segments confirm that the development of an antagonistic torque at the most proximal joint was not beneficial to throwing performance. The forces induced by the action of the negative torque at the shoulder resulted in a decrease in the magnitude of the velocity of the ball from the hand at the time of release.

The second variable which determines the success of the throw is the angle of release of the ball. In the optimal throw with proximal antagonism, it appears that the modified configuration of the segments at release was a mechanism to re-orient the velocity vector in order to compensate for the reduced magnitude of the velocity of the ball. The importance of the orientation of the segments at the time of ball release was also demonstrated in the sub-optimal throw with proximal antagonism. The improvement could not be accounted for by the resultant segmental endpoint velocities or the velocity vectors of the ball at release because they were so similar. The slight improvement was due to the greater height of the ball at release (0.649m compared to 0.627m). Similar results were presented by Kojima (1992). In a simulation of overarm throwing, the distance that a mass of 7.27kg was projected increased with the onset of proximal antagonism. The improvement was due to a modification of the position and direction of the velocity vector at release, but not to an enhanced velocity.

The influence that proximal antagonism had on the optimal and sub-optimal throws indicates that many factors contribute to the final outcome. Success inherently depends upon the magnitude and direction of the velocity vector of the ball and the height of the ball above the ground when it is released from the hand. In trying to meet these criteria, the joint torques must be developed in a timely manner so that optimal segmental motion results. With increasing degrees of freedom in a multisegmental system, there are many different ways of meeting the same objective. The final outcome depends upon the initial conditions of the system, the times of onset of all muscles and the physiological characteristics of the muscles. If one of these factors is less than optimal, there appear to be compensatory effects in order to optimize performance under the conditions which are imposed.

Chapter 5. Sensitivity Analysis

METHODS 3

The sensitivity of throwing performance to changes in the mechanical properities of muscle was determined for four of the parameters used to define the characteristics of muscle. The parameters which were modified include: maximal isometic torque (MMAX), maximal velocity of shortening (VMAX), the angle at which maximal isometric torque is developed (MXOO), and the stiffness of the series elastic component (SEXM). Each of the parameters was varied by +/- 1, 2, 5, 10 and 15 percent. The influence of these changes on throwing performance was evaluated in terms of the range that the ball was projected.

To determine the effect of each of the changes made to each of the parameters (e.g. increasing MMAX by 10 percent), a separate batch of throws was simulated. In each set of simulations, the times of onset and duration of activation of the antagonists were constant and equal to those of the original best throw (Chapter 3). The times of onset of the agonists were varied to allow the model to adapt to each different muscle characteristic and find a new set of times of activation which led to optimal performance. The boundaries defining the times of agonist onset varied from 20ms before to 20ms after the previous best times (0.200, 0.280 and 0.270s).

The other possible simulation strategy would have been to maintain the same times of agonistic onset as were used in the original optimal throw and determine how each change to the muscle characteristics modified performance. This option was rejected for two reasons. Firstly, the ability of the model to make use of potential enhancement derived through changes to the muscle properties would have been restrained by restricting the model to use the previous best times. Secondly, when this approach was used, there were cases in which the criteria which defined limits to joint range of motion or magnitude of torque development were exceeded. In these situations, the throw would have had to have been excluded.

Because the changes made to each parameter were relatively small in magnitude, the search fields used to define the batches associated with each change were small. The range of onset times (s) for each agonist are shown below:

SHOULDER EXTENSOR	ELBOW EXTENSOR	WRIST FLEXOR
0.180	0.260	0.250
↓	↓	↓
0.220	0.300	0.290

Increments of 5ms were used to distinguish between different throws. When all possible combinations of agonistic onset times were generated, 729 throws were produced. The maximal range throw from each batch, within the established limits of range of motion and torque, was identified.

1. *Maximal Isometric Torque (MMAX)*

The absolute values for MMAX for the agonist muscles acting at the shoulder, elbow and wrist are given in Table M3-1.

Table M3-1. Magnitude of MMAX for the shoulder, elbow and wrist agonists.

PERCENT CHANGE	SHOULDER (N.m)	ELBOW (N.m)	WRIST (N.m)
-15	68.00	42.5	12.75
-10	72.00	45.0	13.50
-5	76.00	47.5	14.25
-2	78.40	49.0	14.70
-1	79.92	49.5	14.85
0	80.00	50.0	15.00
1	80.80	50.5	15.15
2	81.60	51.0	15.30
5	84.00	52.5	15.75
10	88.00	55.0	16.50
15	92.00	57.5	17.25

2. *Maximal Velocity of Shortening (VMAX)*

The absolute values for VMAX for the agonist muscles acting at the shoulder, elbow and wrist are given in Table M3-2.

Table M3-2. Magnitude of VMAX for the shoulder, elbow and wrist agonists.

PERCENT CHANGE	SHOULDER ($rad.s^{-1}$)	ELBOW ($rad.s^{-1}$)	WRIST ($rad.s^{-1}$)
-15	23.80	23.80	19.55
-10	25.20	25.20	20.70
-5	26.60	26.60	21.85
-2	27.44	27.44	22.54
-1	27.72	27.72	22.77
0	28.00	28.00	23.00
1	28.28	28.28	23.23
2	28.56	28.56	23.46
5	29.40	29.40	24.15
10	30.80	30.80	25.30
15	32.20	32.20	26.45

3. Joint Angle of Maximal Isometric Torque Development (MXOO)

The absolute values for MXOO for the agonist muscles acting at the shoulder, elbow and wrist are given in Table M3-3.

Table M3-3. Magnitude of MXOO for the shoulder, elbow and wrist agonists.

PERCENT CHANGE	SHOULDER (rad)	ELBOW (rad)	WRIST (rad)
-15	21.25	-26.45	-11.50
-10	22.50	-25.30	-11.00
-5	23.75	-24.15	-10.50
-2	24.50	-23.46	-10.20
-1	24.75	-23.23	-10.10
0	25.00	-23.00	-10.00
1	25.25	-22.77	-9.90
2	25.50	-22.54	-9.80
5	26.25	-21.85	-9.50
10	27.50	-20.70	-9.00
15	28.75	-19.55	-8.50

4. Stiffness of Series Elastic Component (SEXM)

The absolute values for SEXM for the agonist muscles acting at the shoulder, elbow and wrist are given in Table M3-4.

Table M3-4. Magnitude of SEXM for the shoulder, elbow and wrist agonists.

PERCENT CHANGE	SHOULDER (rad)	ELBOW (rad)	WRIST (rad)
-15	21.25	27.20	42.50
-10	22.50	28.80	45.00
-5	23.75	30.40	47.50
-2	24.50	31.36	49.00
-1	24.75	31.68	49.50
0	25.00	32.00	50.00
1	25.25	32.32	50.50
2	25.50	32.64	51.00
5	26.25	33.60	52.50
10	27.50	35.20	55.00
15	28.75	36.80	57.50

RESULTS 3

In all cases, the distance the ball was projected differed from the original best range of 14.778m when the parameters defining the muscle properties were modified. In some cases, the maximal ball range was achieved when the onset times of the agonists were unchanged from those of the original best throw. This tended to occur when the parameters were changed a small amount (+/- 1 or 2 percent). However, in other cases, the agonistic onset times which resulted in maximal performance differed from those of the optimal throw. There are two explanations for the observed changes in timing. The first is that with different muscle characteristics, it was necessary for the behaviour of the model to change in order to maximize the result. Secondly, the limits placed on the range of joint motion of the model remained in effect during this sensitivity analysis. As a result, a particular throw which may have been more successful in terms of projecting the ball a greater range was excluded because it violated the constraints put on the model. All throws presented in these results were within the limits of the model.

The results illustrated in the following figures (Figures R3-1 to R3-4) are from throws in which: (i) a single muscle parameter at a given joint has been modified, (ii) the times of antagonistic muscle onset are the same as those of the original optimal throw, (iii) the times of agonistic onset are those which optimized performance, and (iv) behaviour of the model was within the limits of range of joint motion defined in the model.

A. *Maximal Isometric Torque (MMAX)*

Figure R3-1 illustrates the effect of changing the maximal isometric torque of the shoulder, elbow and wrist agonists on the projected distance of the ball. Throwing performance is most sensitive to changes in the torque producing capabilities of the shoulder, moderately sensitive to changes at the elbow and essentially insensitive to changes in maximal torque of the wrist flexors. In all cases, increases in maximal isometric torque led to an improvement in ball range, and decreases in maximal isometric torque reduced throwing performance.

The changes made to the agonistic onset times in generating the optimal throws shown in Figure R3-1 are given in Table R3-1. The three values are times of onset of the shoulder extensor, elbow extensor and wrist flexor, respectively, with respect to zero time. The empty cells indicate those throws in which optimal performance was achieved with the same times of agonistic onset as were used to generate the original optimal throw (i.e. 0.200, 0.280 and 0.270 s at the shoulder, elbow and wrist, respectively). Changes to maximal isometric torque at the shoulder and elbow had a greater influence on timing than did changes to the maximal torque at the wrist. In general, when the maximal torque producing capability at a joint was reduced (decrease in MMAX), the onset of activation of the muscle crossing that joint was earlier. Similarly, when MMAX was increased, the onset of activation was delayed. The shoulder joint is an exception because of the constraints placed upon the joint range of motion. When the onset of shoulder activation was delayed beyond 0.200s, then the limit of shoulder range of motion was exceeded and the throw was omitted. The timing of onset of activation at the wrist varied considerably when changes were made to MMAX at the shoulder and elbow.

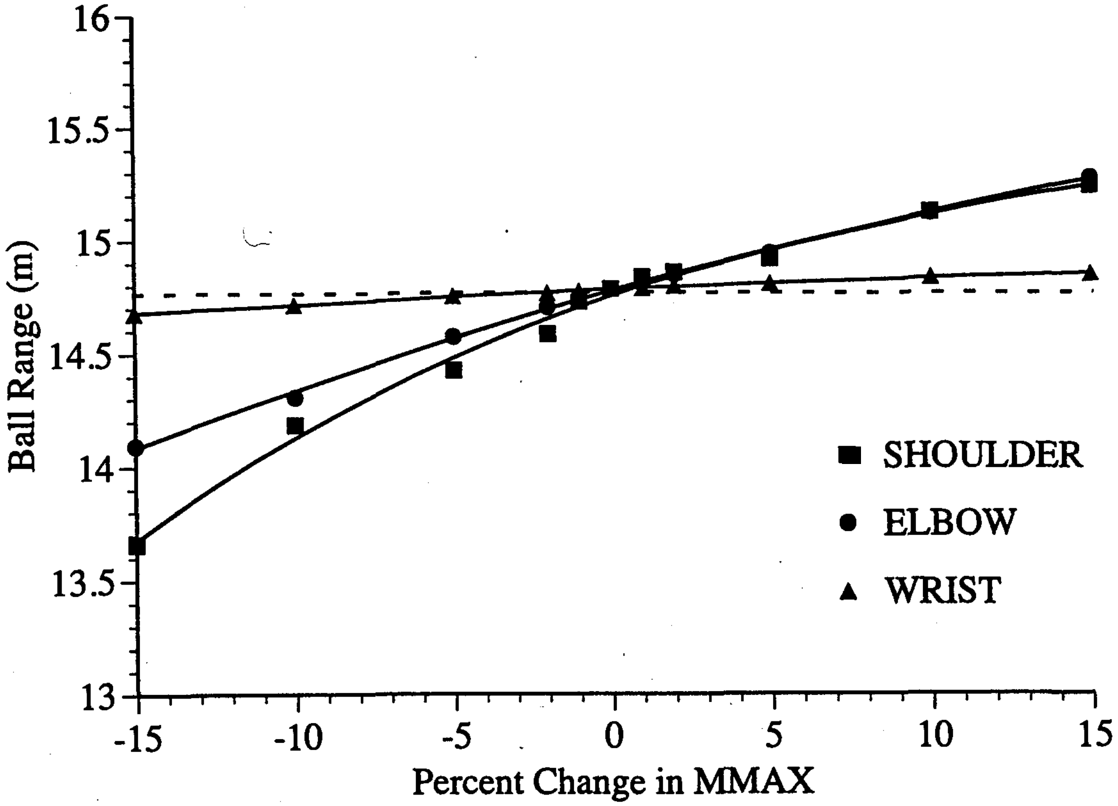


Figure R3-1. The effect of changing the maximal isometric torque (MMAX) of the shoulder, elbow and wrist agonists on the projected distance of the ball.

Table R3-1. Times of onset of shoulder (SH), elbow (EL) and wrist (WR) single equivalent agonists of the best throws during sensitivity analysis of throwing performance to changes in the maximal isometric torque (MMAX) of the shoulder, elbow and wrist.

PERCENT CHANGE	SHOULDER MMAX			ELBOW MMAX			WRIST MMAX		
	TIME OF ONSET			TIME OF ONSET			TIME OF ONSET		
	SH	EL	WR	SH	EL	WR	SH	EL	WR
-15	0.190	0.275	0.285	0.200	0.275	0.260	0.200	0.280	0.265
-10	0.195	0.280	0.280	0.200	0.280	0.280	0.200	0.280	0.265
-5	0.195	0.280	0.290	0.200	0.280	0.275	0.200	0.280	0.265
-2	0.195	0.275	0.270						
-1									
1				0.200	0.280	0.265			
2	0.200	0.280	0.275						
5	0.200	0.275	0.265	0.200	0.280	0.265			
10	0.200	0.275	0.260	0.200	0.285	0.285			
15	0.200	0.275	0.260	0.200	0.285	0.285	0.200	0.280	0.275

B. Maximal Velocity of Shortening (VMAX)

The effect of changing the maximal velocity of shortening of each agonistic muscle on ball range is shown in Figure R3-2. Performance was most sensitive to changes in the shoulder extensor, less sensitive to changes in the elbow, and essentially insensitive to changes in the wrist flexor. In all simulated throws, ball range was increased when the maximal velocity of shortening of the agonists was increased.

The timing of agonistic muscle activity at all joints was affected by changes to the shoulder maximal velocity (Table R3-2), although the time of onset of the wrist flexor was influenced the most. When VMAX at the elbow and wrist was modified, timing was affected in an equal number of throws; however, only the time of onset of the wrist flexor was affected by changes to VMAX at these two joints. In general, changes in timing were necessitated only by large changes to this muscle property.

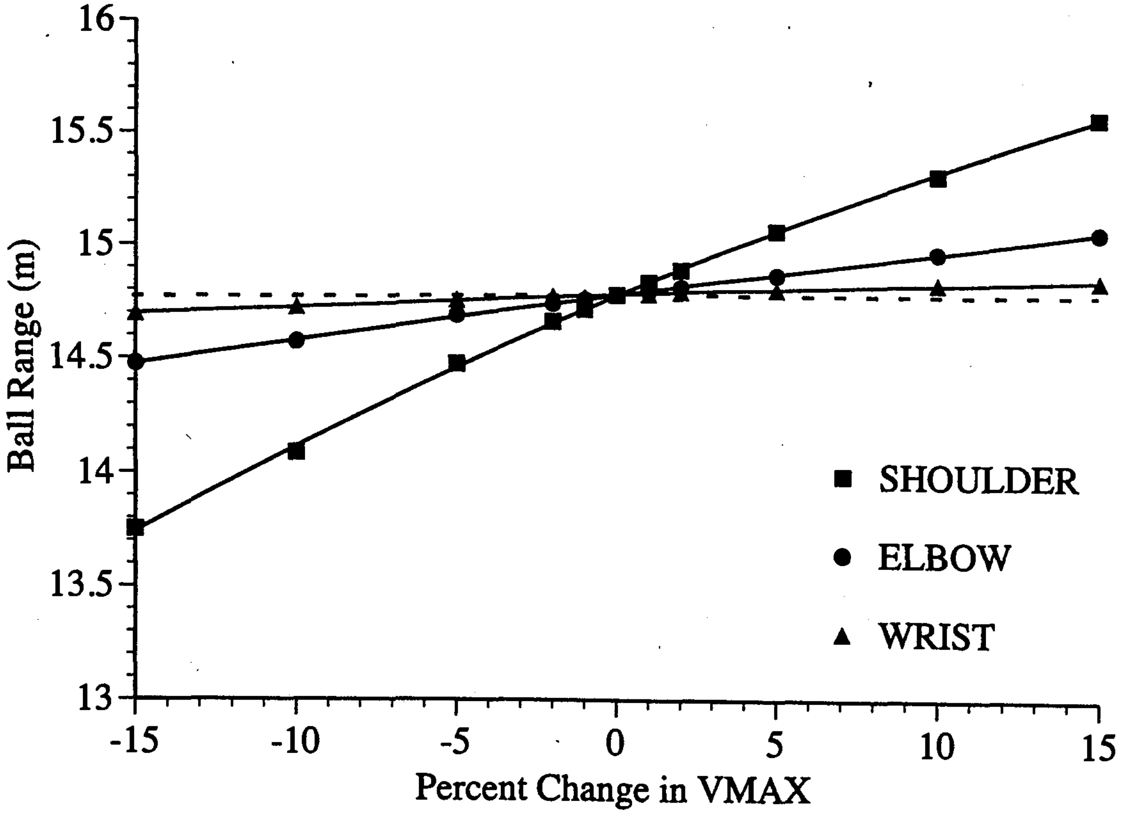


Figure R3-2. The effect of changing the maximal velocity of shortening (VMAX) of each agonistic muscle on ball range.

Table R3-2. Times of onset of shoulder (SH), elbow (EL) and wrist (WR) single equivalent agonists of the best throws during sensitivity analysis of throwing performance to changes in the maximal velocity of shortening (VMAX) of the shoulder, elbow and wrist.

PERCENT CHANGE	SHOULDER VMAX			ELBOW VMAX			WRIST VMAX		
	TIME OF ONSET			TIME OF ONSET			TIME OF ONSET		
	SH	EL	WR	SH	EL	WR	SH	EL	WR
-15	0.195	0.280	0.290	0.200	0.280	0.275	0.200	0.280	0.265
-10	0.195	0.275	0.265	0.200	0.280	0.275	0.200	0.280	0.265
-5	0.200	0.280	0.265				0.200	0.280	0.265
-2	0.200	0.280	0.265						
-1									
1									
2									
5									
10	0.200	0.280	0.275	0.200	0.280	0.265			
15	0.200	0.280	0.275	0.200	0.280	0.265	0.200	0.280	0.275

C. Joint Angle of Maximal Isometric Torque Development (MXOO)

The angle at which maximal isometric torque is generated has little influence on maximal throwing performance (Figure R3-3). Of the three muscles in which this characteristic was modified, changes to the elbow extensor had the greatest effect.

The minimal effect that changes to this property had on throwing is reinforced in Table R3-3. The results indicate that the behaviour of the system did not have to compensate for the changes made to the muscles in terms of timing of onset of the agonists. The only modification made to the timing of agonist onset was earlier activation of the wrist flexor in two throws.

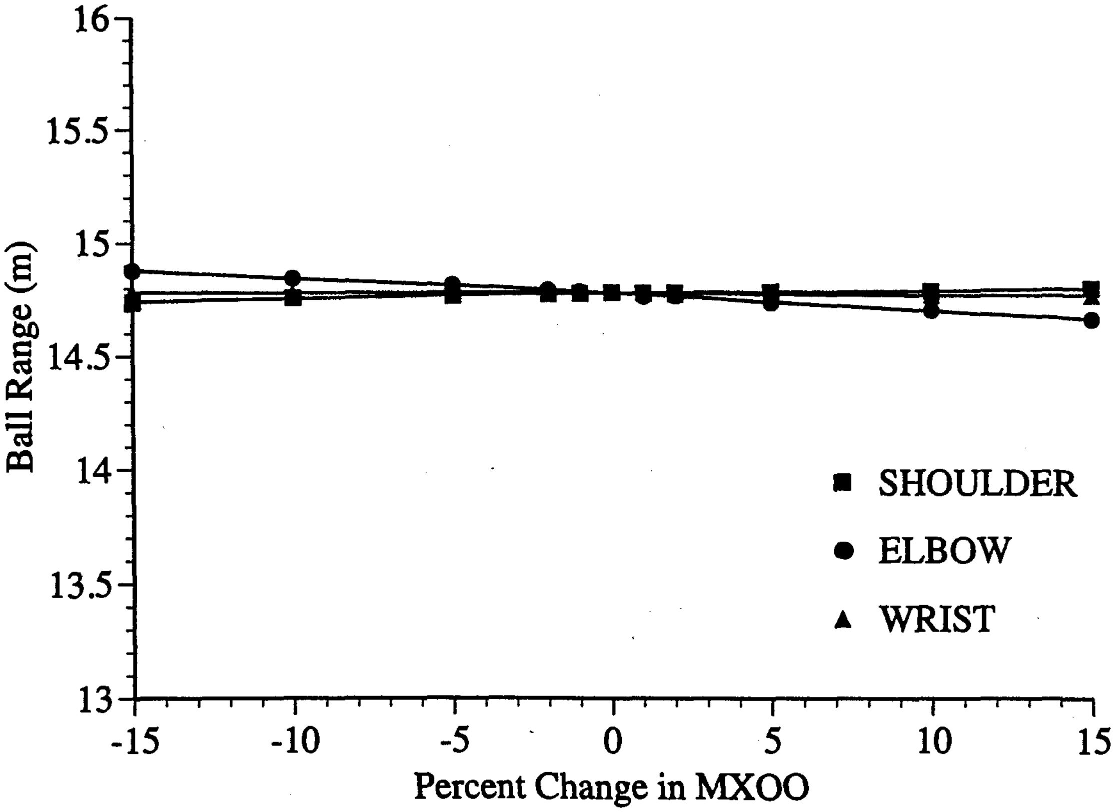


Figure R3-3. The effect of changing the angle of maximal isometric torque (MXOO) of each agonistic muscle on ball range.

Table R3-3. Times of onset of shoulder (SH), elbow (EL) and wrist (WR) single equivalent agonists of the best throws during sensitivity analysis of throwing performance to changes in the angle of maximal torque development (MXOO) of the shoulder, elbow and wrist.

PERCENT CHANGE	SHOULDER MXOO			ELBOW MXOO			WRIST MXOO		
	TIME OF ONSET			TIME OF ONSET			TIME OF ONSET		
	SH	EL	WR	SH	EL	WR	SH	EL	WR
-15				0.200	0.280	0.265			
-10									
-5									
-2									
-1									
1									
2									
5									
10	0.200	0.280	0.265						
15									

D. Stiffness of the Series Elastic Component (SEXM)

The final property of muscle which was modified was the stiffness of the series elastic component. Ball range was most sensitive to changes in the series elastic stiffness of the elbow extensor (Figure R3-4). Changes made to this property in the shoulder and wrist agonists had little effect on throwing performance. Increases to the magnitude of SEXM correspond to reduced SEC stiffness; therefore, the results shown in Figure R3-4 indicate that greater ball ranges occurred when the stiffness of the elbow extensor SEC was reduced.

Although throwing performance was minimally affected by changes to the series elastic stiffness, the behaviour of the system was modified considerably to compensate for the changes made to the muscle (Table R3-4). Changes to the agonistic onset times were required in the majority of the simulated throws, although timing was affected primarily by changes to the shoulder muscle. At the shoulder, when the SEC stiffness was decreased, the onset of shoulder extension was advanced relative to the previous onset time. An increase in SEC stiffness of the shoulder did not result in a delay of the time of onset of activation because of the limits imposed upon shoulder range of joint motion. Onset times beyond 0.200s resulted in excessive shoulder flexion and the exclusion of the throw. Changes to the stiffness of the SEC at the elbow and wrist resulted in changes in timing of activation of the wrist only. The timing of the shoulder and elbow was unaffected.

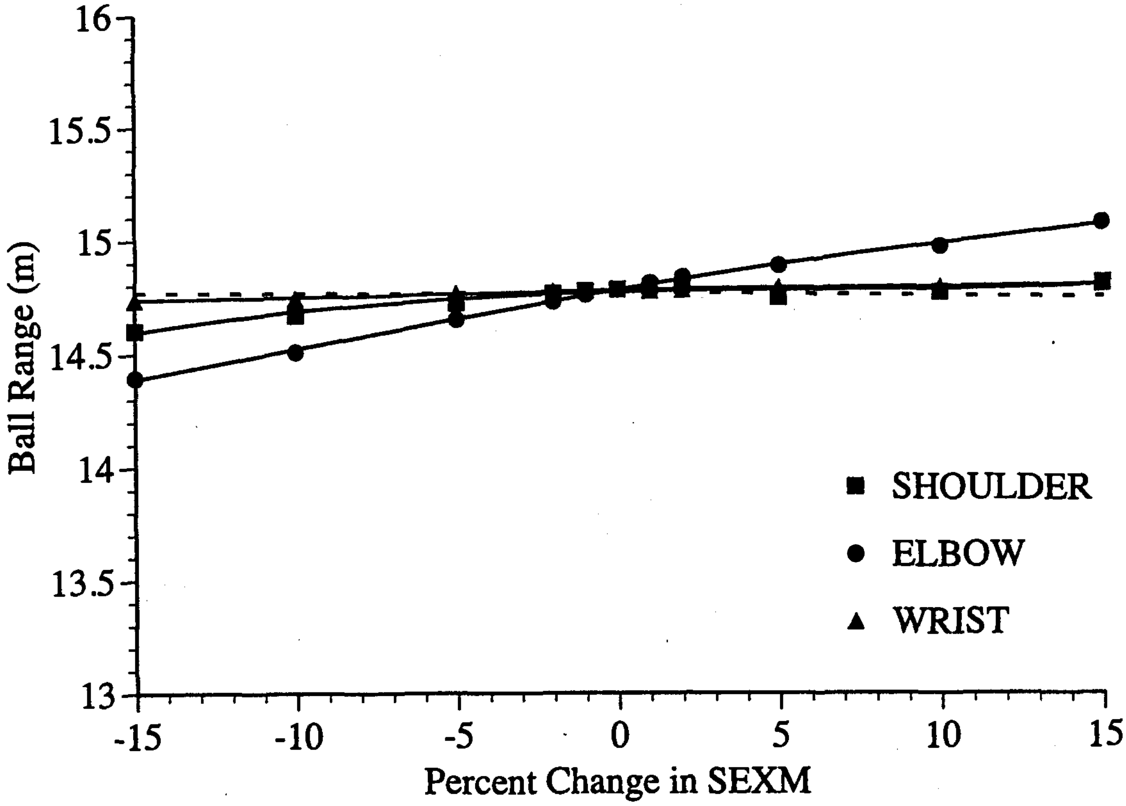


Figure R3-4. The effect of changing the stiffness of the series elastic component (SEXM) of each agonistic muscle on ball range.

Table R3-4. Times of onset of shoulder (SH), elbow (EL) and wrist (WR) single equivalent agonists of the best throws during sensitivity analysis of throwing performance to changes in the stiffness of the series elastic component (SEXM) of the shoulder, elbow and wrist.

PERCENT CHANGE	SHOULDER SEXM			ELBOW SEXM			WRIST SEXM		
	TIME OF ONSET			TIME OF ONSET			TIME OF ONSET		
	SH	EL	WR	SH	EL	WR	SH	EL	WR
-15	0.200	0.280	0.290	0.200	0.280	0.275	0.200	0.280	0.265
-10	0.200	0.280	0.280				0.200	0.280	0.265
-5	0.200	0.280	0.275						
-2				0.200	0.280	0.265			
-1				0.200	0.280	0.265			
1	0.200	0.280	0.265						
2	0.200	0.280	0.265						
5	0.195	0.275	0.265	0.200	0.280	0.275	0.200	0.280	0.265
10	0.195	0.275	0.265	0.200	0.280	0.280	0.200	0.280	0.265
15	0.195	0.275	0.265	0.200	0.280	0.280	0.200	0.280	0.265

For a given percentage change, each parameter differentially affected throwing performance. The influence of changes to maximal isometric torque (MMAX) and maximal shortening velocity (VMAX) was approximately the same. The relative influence is distorted somewhat because of the fact that changes to the times of agonist onset also influence the results. In addition, throws which projected the ball a greater distance than the distance that was recorded in the results were eliminated in some cases because the limits of the range of motion were exceeded in those throws. However, when all factors are considered, throwing performance is more sensitive to changes in MMAX. The third most sensitve parameter is the stiffness of the series elastic component (SEXM). Throwing performance is least sensitive to the angle at which maximal isometric torque is developed (MXOO).

DISCUSSION 3

The results indicate that throwing performance can be modified by changing the physical characteristics of the muscles which participate in the action. The greatest influence was brought about by changes to the those properties which directly influence the force generating capabilities of the muscle, i.e. maximal isometric torque and maximal velocity of shortening. Throwing performance was influenced less by those characteristics which indirectly influence force production in muscle, i.e. the joint angle at which maximal isometric torque is developed and the stiffness of the series elastic element.

The torque-angular velocity relationship of muscle was the dominant characteristic in terms of bringing about improvements in throwing performance. The torque profiles depicted in Chapters 3 and 4 indicate the importance of the application of a large impulse immediately following the onset of each agonistic muscle. A greater impulse can be generated if the maximal force generating capability of a muscle is greater (MMAX) or if a muscle is able to generate more force at a given velocity of shortening (VMAX). The torque profiles also indicate that after maximal torque is developed, a reduction in torque occurs concurrently with an increase in joint angular velocity. An enhanced torque-angular velocity relationship would decrease the attenuation and prolong the torque producing capability of the muscle.

The angle at which peak isometric torque was developed (MMAX) had little influence of throwing performance. This is due to the relatively flat nature of the isometric torque-angle relationship of muscle.

The increase in throwing performance that occurred with a decrease in stiffness of the series elastic component of the elbow extensor was surprising. In previous work with a similar model, Chapman (1985) reported that with a stiffer SEC, the rate of rise in force in an isometric contraction was greater. This was accounted for by a reduced rate of shortening of the contractile component, maintaining it on a favourable region of the force-velocity relationship. Pousson et al. (1990) reported an increase in stiffness of the series elastic component in eccentrically trained elbow flexors, acting as a single equivalent muscle. It was suggested that this change would favour the release of potential energy during stretch-shortening contractions because the time between stretching and shortening would be reduced. In this thesis, the improved throwing performance associated with a decrease in elbow extensor series elastic stiffness was accounted for by an increase in the amount of work done by the contractile component (Figure D3-1). More work was done because the contractile component operated over a greater angular excursion.

Changes to the muscle properties at the shoulder had a consistently greater effect than did changes to the muscles at the elbow and wrist, (Figures R3-1, R3-2 and R3-4). Although the relative change in magnitude of each parameter was equal for all muscles, the absolute difference was greater at the shoulder. Because more successful throws were characterized by a greater percentage of work done by the shoulder extensor than the other muscles (Figure R1-2), it is more advantageous to improve the work producing capacity of the shoulder than of the elbow or wrist. The only exception to this was that changes to the stiffness of the series elastic component of the elbow extensor had a greater influence on performance than did changes to that of the shoulder or wrist agonists. This could be related to the fact that the elbow joint undergoes the greatest range of angular range of motion during a throw.

In general, the greater influence that a change in a muscle parameter had on performance (ball range), the more the behaviour of the system had to adapt to account for the changes (Tables R3-1 through R3-4). This indicates if a muscle were to improve its torque generating capabilities without also modifying the timing of agonistic muscle onsets during a throw, then the potential benefit would not be realized.

The implication of these results is three-fold. Firstly, the results indicate the significance of individual differences in muscle properties in determining one's success in

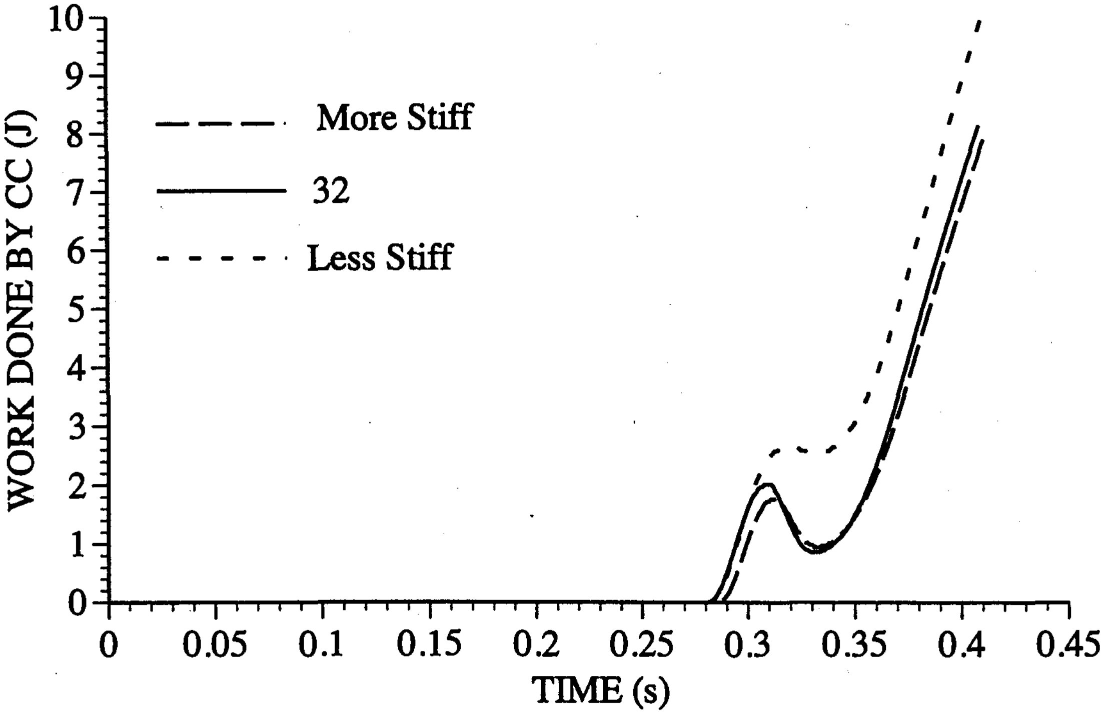


Figure D3-1. Work done by the elbow extensor contractile component (CC) in throws with three different values of SEC stiffness.

the execution of a multisegmental skill. A stronger person will be able to throw a ball farther than a weaker person, provided that both individuals optimize the segmental timing and sequencing. The significance of this is that the technique that a particular athlete adopts should be tailored to their physical capabilites. This is also supported by the fact the timing of onset of the agonists adapted to changes in each characteristic, especially when the percentage change was large (+/- 10 or 15 percent), as shown in Tables R3-1 through R3-4.

The second implication of the dependence of performance on the physical characteristics of muscle is that muscle training can be advantageous. The net torque profiles at the shoulder and elbow, in particular, indicate that large impulses are desirable immediately following the onset of activation. Dynamic training, particularly stretch-shortening exercises, would be most beneficial for improving throwing performance because the necessary muscular power can be enhanced with appropriately designed training regimens.

In addition to the significance of the results in terms of application to human coordination, the findings are also applicable to future modelling efforts. Having identified that performance is largely sensitive to the torque-angular velocity relationship of muscle and somewhat sensitive to the stiffness of the series elastic component, it is important that the parameters defining these properties of all muscles are acurately defined in future models.

In spite of the observed influence of changes to the physical properties of muscle on throwing performance, it appears that coordinated motion resulting from optimal timing and sequencing of segmental motion is of greater underlying importance. It is difficult to quantify the relative importance of each. While it is straight-forward to modify muscle strength by +/- 5 percent, the same approach could not be used in changing the times of onset of each muscle model. However, the range in success of performance observed in throws produced by many combinations of agonistic onset times (Figure R1-

1), indicates the ease with which a very unsuccessful throw can be generated. On the other hand, if successful technique is used, and there is a minor decrement in the capabilities of the muscle, reasonable throwing performance can still be achieved.

Chapter 6
CONCLUSIONS AND RECOMMENDATIONS

Computer modelling and simulation have been used in place of experimentation with human subjects to investigate the contribution of muscle to successful performance in a multisegmental skill. Simple, planar overarm throwing was selected for analysis. Repeated simulations were performed until the optimal timing and sequencing of onset of activation of the three agonistic and three antagonistic muscles were identified. Optimal timing was defined as that which resulted in a ball being projected a maximal distance from the hand segment. The patterns of segmental behaviour and muscular torque production during the optimal throw were investigated in order to determine the mechanisms underlying its success. This was achieved, in part, by comparing segmental and muscular behaviour during the most successful throw with that of throws which resulted in sub-maximal performance.

The importance of appropriate timing of activation of all muscles for achieving success was made evident when a large group of throws was compared in Chapter 3. Differences in timing resulted in throwing performance ranging in success from poor throws, with a projected ball distance of 6m to successful throws which projected the ball distances greater than14m. The importance of timing was also indicated in Chapter 5 when the sensitivity of throwing success to changes in the physical characteristics of muscle was investigated. When the parameters defining the torque-producing characteristics of muscle were modified, the timing of agonist onset was often forced to adjust in order to account for the altered properties of muscle and optimize the behaviour of the system.

Having established that the timing of activation of the muscles is a critical determinant of the success of a throw, it remained to be determined why this was the case.

Previous work by Herring (1989) indicated that the physical characteristics of the segments within a multilink system predispose it to following the proximal to distal sequencing of segmental motion which has been observed in many skills. This indicated that regardless of the physiological properties of muscle, the system behaved optimally with a proximal to distal sequencing of onset of three agonists. The current model was developed to determine how the known mechanical characteristics of muscle influence the behaviour of the system.

The approach used by Herring (1989) was successful because it was possible to remove the physiological properties of muscle from a multisegmental model and provide muscular input to the system with constant torque generators. The torques produced were independent of length and velocity. This allowed the study of the influence of the segmental properities in isolation from known physiological muscular properties. However, in the current thesis, the reverse was not possible. It is impossible to study the influence of the characteristics of muscle on multisegmental motion without segments for the muscles to act upon. As a result, determining the contribution of muscle to the resulting behaviour of the system was complex because of the interaction of muscular and segmental factors.

The behaviour of the system during an optimal throw in this thesis differed from that in Herring (1989). Using the current model, in the optimal throw neither the onsets of the three agonists nor the timing of occurence of peak joint angular velocity occurred in a proximal to distal sequence. The most important determinant of success was that there was a large increase in energy in the hand segment late in the throw. The role of muscle in bringing this about is illustrated in the work and power profiles associated with the optimal throw. The generation and transfer of energy in the proximal to distal direction within the linkage was evident and necessary for success.

The interaction of segmental and muscular effects was implicated primarily in two specific aspects of the model. The first is that segmental patterns of motion and the timing of onset of the agonists allowed the benefits of the stretch-shortening cycle of muscle contraction to be realized. As a result, greater muscular torques were developed earlier, providing a greater impulse to the system. The second implication of the physiological characteristics of muscle being incorporated into the model was the large influence of the torque-angular velocity relationship. This was demonstrated both in the results of the optimal throw (Chapter 3) and in the sensitivity analysis of the characteristics of muscle (Chapter 5). The properties of muscle to which performance was most sensitive were the maximal isometric torque and the maximal velocity of shortening of muscle.

The suggestion that performance can be improved by developing an antagonistic torque at the most proximal joint was refuted (Chapter 4). In nearly all cases, proximal antagonism led to a decrement in throwing performance. This was attributed to the configuration of the segments during the throw, whereby the forces applied at the joints resulted in backward or reduced accelerations of the segmental centres of mass relative to the direction of the throw. In the few throws in which ball range increased with shoulder antagonism, the improvement was due to the orientation of the segments at the time of release rather than to an increase in the velocity of the ball.

All results and conclusions must be interpreted within the limitations of the model. The ultimate goal of understanding muscular and segmental contributions to coordinated multisegmental motion in humans requires further development of the model. One modification which should be made is the incorporation of bi-articular muscles. With the development of imaging and modelling techniques, the influence of all muscles could eventually be incorporated. The second necessary modification is to address the three dimensional nature of most throwing activities and incorporate the contribution of segments which are proximal to the arm. These refinements, as well as more precise modelling of the existing elements will allow a better understanding of the complex interactions of the neural, muscular and segmental characteristics involved in skilled motion and may eventually provide insight into the nature of control of the system.

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APPENDIX A
MUSCLE MODEL PARAMETERS

Each muscle model used to generate the torques during the simulated throws comprised three elements: the contractile component, and the series and parallel elastic components. The characteristics of the contractile component were defined by the isometric torque-angle relationship and the torque-angular velocity relationship, both of which are a function of the level of activation. The two elastic components were each defined by a non-linear torque-angle relationship. In order that the same general equations defining each of the above relationships could be applied to the six different muscles included in this model, the values of the parameters used in the equations were varied according to data obtained experimentally and reported in the literature.

In total, fourteen parameters were defined for each muscle model. Since the equations describing each relationship were originally defined by Winters (1985), where possible, the original values which he provided for each parameter were used. When the values provided by Winters were not in agreement with data reported in the literature, they were modified accordingly. Winters did not include any information regarding shoulder flexion or extension; therefore, all parameters describing the shoulder muscles were obtained from either measurement or published data.

All values were given in Table M2 and the resulting relationships for each muscle have been depicted in Figures M3 through M8. This Appendix will provide the sources used to derive the chosen values of each parameter. Generally speaking, it was difficult to find suitable data for two reasons. Firstly, the convention used to define joint angles was often not given, therefore, the published data were of no use. Secondly, the elbow joint has been studied frequently, however, there is considerably less information available regarding the shoulder and wrist joints. As a result, some of the parameters were extrapolated using the limited information that was available. In those cases in which no information is given in this appendix regarding a particular parameter, the value used was that provided by Winters (1985).

CONTRACTILE COMPONENT TORQUE-ANGLE RELATIONSHIP

(MXOO, MMAX, MXSH)

Shoulder:

Little information is available regarding isometric shoulder extension and flexion strength. Ivey et al. (1984) reported isokinetic torques at the shoulder during slow (60 deg.s^{-1}) and fast (180 deg.s^{-1}) contractions. At both speeds, extension strength was greater than flexion by a ratio of 5:4. Maximal extension strength was 78 Nm at an angle of 83 degrees, where 0 degrees is defined with the hand next to the thigh and 180 degrees with the hand overhead. A maximum of 61 Nm of flexion occurred at an angle of 97 degrees.

During shoulder flexion isometric contractions at three different angles, the resulting torques ranged from 75 to 94 Nm in the dominant arm (Otis et al., 1990). A summary of human strength curves has been published by Kulig et al. (1984). Shoulder flexion strength was shown to decrease from a maximum ranging from 350 to 500 N in full extension to approximately 125 N in full flexion. The shoulder extension force-angle curve resembled more closely the inverted U-shape relationship that is commonly reported. A maximum ranging from 350 to 450 N occurred near the mid-region of shoulder range of motion. It should be noted that these results do not take into account the muscle moment arms which vary with joint angle.

Elbow:

The elbow has been the most widely studied joint in the arm. This is beneficial in terms of the quantity of data which are available, however, the limitation is that there is much variability in the results. For example, the angle at which maximal extension torque has been reported to occur varies from 10 degrees of extension (Singh and Karpovich, 1966), to 15 degrees of extension (Hortobagyi and Katch, 1990) to 45 degrees of extension (Hatze, 1981) where 0 degrees is defined as the forearm being perpendicular to the upper arm. There is also variability in the results concerning elbow flexion. Most of the data indicate that the angle of peak torque occurs at approximately 15 degrees of flexion (Hasan and Enoka, 1985a; Singh and Karpovich, 1966; Van Zuylen et al., 1988). However, there are exceptions which range from 15 degrees of extension (Hortobagyi and Katch, 1990) to 90 degrees (An et al., 1989).

The values of maximal isometic torque during elbow extension and flexion used in this thesis were the same as those reported in Winters (1985). However, it should be kept in mind that the magnitude of the torque produced during elbow extension and flexion depends upon the angle of rotation of the forearm, i.e. the degree of supination or pronation. In sagittal overarm throwing, the forearm is fully pronated. One study which did distinguish between isometric elbow flexor torque measured in pronation, supination and a neutral forearm angle found that greater maximal torques were produced in the neutral position regardless of the elbow angle (Caldwell and VanLeemputte, 1991). When the elbow was more flexed (40 degrees of flexion compared to 10 degrees of extension), the fully supinated forearm produced higher elbow flexor torques than did a fully pronated forearm. Conversely, when the elbow was more extended, it was advantageous to fully pronate the forearm.

Wrist:

The study which investigated the characteristics of the wrist musculature in the greatest detail was by Lehman and Calhoun, (1990), although their results were limited to only three subjects. The variability between subjects was quite large, but in general, the isometric torque-angle relationship reported for the wrist flexors and extensors was in agreement with the data given in Winters (1985).

CONTRACTILE COMPONENT TORQUE-ANGULAR VELOCITY RELATIONSHIP (MVVM)

Shoulder:

In addition to providing values for each of the parameters used in the equations describing the characteristics of the single equivalent muscles, Winters (1985) also described a protocol for calculating these values for muscles at joints which were not included. This approach was based on the premise that information about all of the muscles comprising the single equivalent muscle was known (e.g. fibre composition, origin-insertion locations, fibre pennation and length, physiological cross-section, tendon length and moment arm) and could be combined into a single value. The success of this depends on the availability of the required information.

One of the parameters required to describe the torque-angular velocity relationship is the maximal velocity of shortening. This magnitude of this parameter is dependent upon the proportion of fast and slow twitch muscle fibres in the muscles crossing the joint. Johnson et al., (1973) reported a higher percentage of slow twitch fibres in the shoulder flexors than in the shoulder extensors.

Elbow:

The values used in this thesis regarding the torque-angular velocity relationship for the elbow extensors and flexors are the same as those presented by Winters (1985). The lower magnitude of maximal velocity of shortening of the elbow flexors is in agreement with Jorgensen (1976).

Wrist:

The magnitude of the maximal velocity of shortening of the wrist flexors and extensors used in this thesis were also the same as those reported in Winters (1985). There is little relevant information in the literature concerning the torque-angular velocity relationship at the wrist. Lehman and Calhoun (1990) reported a maximal velocity of shortening of the wrist flexors which agreed with that of Winters (1985), however, the value given for the wrist extensors was considerably lower. The fibre composition information reported by Johnson et al. (1973) is limited to the extensor digitorum and flexor digitorum muscles, and the percentage of slow twitch fibres in these two muscles was equivalent.

PARALLEL ELASTIC COMPONENT

(PEXM, PESH)

The parallel elastic component was modelled to represent both the ligamentous structures as well as bony constraints. As a result, this element served somewhat different roles at the different joints. In all joints, the parallel elastic component developed essentially no torque in the central region of joint range of motion. This is in agreement with all reported literature. However, it is at the limits of the joint range of motion that the behaviour of this element differs across joints. Firstly, during overarm throwing, the shoulder joint never approaches the extreme limit of extension; therefore, in the current model, the role of the shoulder flexor PEC was considered to be inconsequential. The same is true for maximal wrist flexion. During the motions of shoulder flexion and wrist extension, passive torque begins to develop gradually as the joint approaches the limit of the range of motion, then increases rapidly at the extremes. The elbow joint differs from the shoulder and wrist in this respect because there is virtually no parallel elastic contribution until the extreme limit of the range of motion. The other difference is that at the limits, the torque at the elbow is due primarily to bony constraints (in extension) and to bony constraints and muscle mass (in flexion). As a result, the nature of the torque-angle relationship at the three joints is different. These differences in shape were achieved by modifying the magnitude of the parameter, PESH in the equations defining this relationship.

In developing these relationships, the magnitude of two other parameters also had to be determined. The first was the angle at which maximal torque was developed (PEXM) and the magnitude of the maximal torque. In Winters (1985), it was assumed that the parallel elastic component developed as much torque passively as the contractile element developed actively (i.e. MMAX). However, reports in the literature indicated that the contribution of the parallel elastic component was considerably less than MMAX. As a result, the maximal torque developed in the parallel elastic component was defined as one third of MMAX.

Shoulder:

The active range of motion at the shoulder joint was measured by Murray et al., (1985). In flexion, the shoulder rotated between 170 and 175 degrees, where 0 degrees is defined as the arm beside the thigh, and 180 degrees is defined by the arm overhead. In extension, the arm rotated approximately 60 degrees.

Elbow:

At the elbow, range of motion in flexion is limited primarily by the mass of the biceps muscle. The angle at which full flexion occurs is between 75 and 80 degrees of flexion, where 0 degrees is associated with the forearm being perpendicular to the upper arm. In extension, the arm is unconstrained until it reaches full extension. This characteristic was achieved in the torque-angle relationship of the parallel elastic component by making the corner of the curve very sharp as the elbow reached full extension.

Wrist:

Lehman and Calhoun's (1990) results were used to define the torque-angle relationship of the wrist flexors and extensors. In the middle of the range of motion (+/- 40 degrees), the torques were reported to be near zero. Torques were not measured beyond 75 degrees of flexion or extension, but the maximal torque recorded was less than 1 N.m. This is significantly lower than that suggested by Winters (1985).

SERIES ELASTIC COMPONENT

(SEXM, SESH)

The magnitudes of SEXM and SESH for the wrist and elbow are unchanged from those presented by Winters (1985).

Shoulder:

There was essentially no information in the literature regarding the property of the series elastic component for the musculature across the shoulder joint. Winters (1985) indicated that the relationships presented in his thesis are more a function of geometry than of any material property considerations. For example, "a muscle twice as long will exhibit a compliance twice as great, and a muscle with twice as large a moment arm will have half as large a compliance value. Larger, two-joint muscles also tend to have more tendon, which keeps the compliance low since tendon is less compliant than muscle," (p.281). At the shoulder, the muscles generally have short tendons and large moment arms. The values used to define the peak extension of the shoulder SEC are between those of the elbow and wrist.

APPENDIX B

EQUATIONS USED IN MECHANICAL ANALYSES

The following equations are based on the conventions and definitions shown in Figure B1.

1. RESULTANT LINEAR ENDPOINT VELOCITIES

Elbow:

$$\dot{x}_e = L1 * \cos\Theta 1 * \dot{\Theta}1$$
$$\dot{y}_e = -L1 * \sin\Theta 1 * \dot{\Theta}1$$
$$v_e = \sqrt{\left(\dot{x}_e^{\,2} + \dot{y}_e^{\,2}\right)}$$

Wrist:

$$\dot{x}_w = \dot{x}_e + L2 * \cos(\Theta 1 + \Theta 2) * \left(\dot{\Theta}1 + \dot{\Theta}2\right)$$
$$\dot{y}_w = \dot{y}_e - L2 * \sin(\Theta 1 + \Theta 2) * \left(\dot{\Theta}1 + \dot{\Theta}2\right)$$
$$v_w = \sqrt{\left(\dot{x}_w^{\,2} + \dot{y}_w^{\,2}\right)}$$

Fingertip:

$$\dot{x}_f = \dot{x}_w + L3 * \cos(\Theta 1 + \Theta 2 + \Theta 3) * \left(\dot{\Theta}1 + \dot{\Theta}2 + \dot{\Theta}3\right)$$
$$\dot{y}_f = \dot{y}_w - L3 * \sin(\Theta 1 + \Theta 2 + \Theta 3) * \left(\dot{\Theta}1 + \dot{\Theta}2 + \dot{\Theta}3\right)$$
$$v_f = \sqrt{\left(\dot{x}_f^{\,2} + \dot{y}_f^{\,2}\right)}$$

2. *MUSCULAR WORK*

$$\text{WORK} = \int \text{TORQUE}\, d\Theta$$

3. *SEGMENTAL ENERGY:*

Total Segmental Energy = Translational Kinetic Energy (TKE)
\+ Rotational Kinetic Energy (RKE)
\+ Potential Energy (PE)

Where

$$\text{TKE} = \tfrac{1}{2}\left(m v_{cm}^{2}\right)$$

$$\text{RKE} = \tfrac{1}{2}\left(I_{cm}\dot{\Theta}^{2}\right)$$

Where

m = *mass of segment*
v_{cm} = *resultant velocity of centre of mass of segment*

I_{cm} = *segmental moment of inertia about centre of mass*
$\dot{\Theta}$ = *segmental angular velocity*

4. POWER:

(refer to Figure B1-b)

Muscle Moment Power:
(for a distal segment)

$$\mathrm{MMP} = \mathrm{TORQUE} * \dot{\Theta}$$

Joint Force Power:

(for a distal segment)

$$\mathrm{JFP} = (F_x * \dot{x}) + (F_y * \dot{y})$$

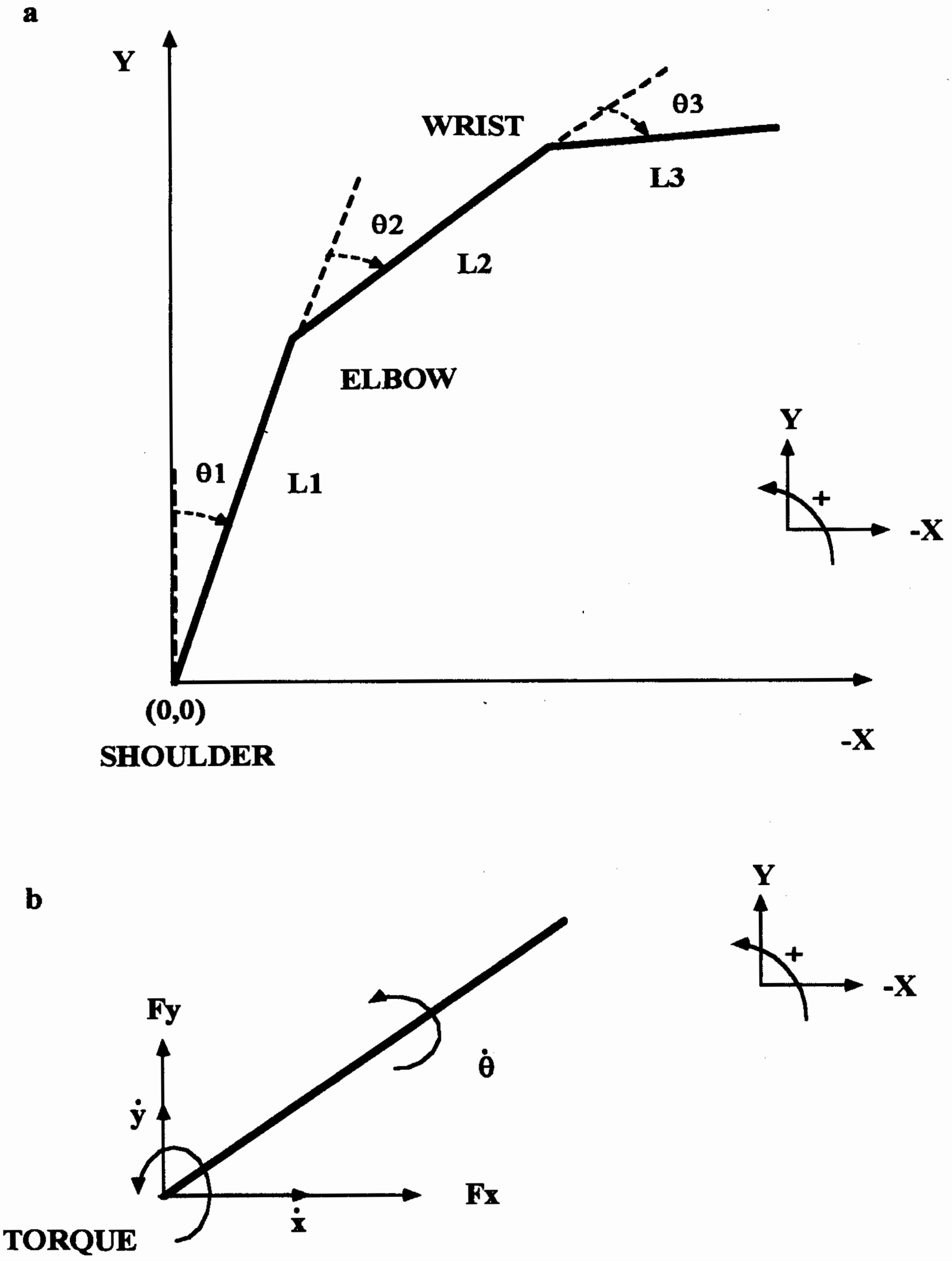

Figure B1. (a) Three segment model of the arm indicating joint angular and segment length conventions used in kinematic and kinetic analyses. (b) A single distal segment showing conventions used in power calculations.