A DIRECT APPROACH TO LANDING IN HUMANS: IMPLICATIONS OF THE TIME-TO-CONTACT VARIABLE AS A MODULATOR OF THE VOLUNTARY TIMING RESPONSE DURING FREE-FALLS.

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ABSTRACT

A new approach in the perceptual-motor behavior field has recently evolved, based mainly on the early work of J.J. Gibson. His concepts led to the view that animal and environment constitute a synergy, while action and perception interact as a functionally constrained unit. Following these concepts, this study investigated a landing task (self-release falls) to assess the extent to which visual information (specifically: the **T** heuristic proposed by D. N. Lee) is effective in the landing preparation. Six subjects performed 48 landings in vision and no-vision conditions (24 trials each) from 5-10, 20-25, 60-65, and 90-95 cm heights of fall categories. The results suggest that the **T** model is not applicable in this task (this was assessed by onset of EMG activity). Rather, subjects, in both visual condition used a "linear strategy" as indicated by the EMG initiation related to the moment of release. In addition, vision does not seem to enhance the ability to reduce the vertical components of ground reaction forces. No differences between 'conditions' were found when the second peak (PSP) and the time to peak (TSP) were the dependent variables (*F*(1,5) =3.68, *p* =.112; and *F*(1,5) =.82, *p* =.409, respectively). Surprisingly, when the analysis was done on the first peak (PFP) the results yielded a main effect for the 'condition' factor, in that the mean PFP magnitude was higher when vision was available

(*F*(1,5) =6.57, *p* =.049). The time to first peak (TFP) was not affected by the visual condition (*F*(1,5) =.13, *p* =.733), thus higher PFP were obtained in vision compared to blindfold landings within the similar time periods. Blindfolded subjects seemed to prepare their actions in advance (EMG activity 250 msec *before release*) in a larger proportions of trials suggesting that they were ready to land. When subjects could see, they generally did not prepare before the initiation of the fall, thus higher PFP were obtained for those trials. It is regarded as feasible that when vision was occluded performers were able to achieve a visual representation of the environment based on prior observation of the height. This information may be useful to time the response during the flight. In addition to this findings, blindfolded subjects showed a larger percentage of activity in an unrelated landing muscle (frontalis) compared to self-release trials in which vision was allowed (*F*(1,5) =13.47, *p*=.001). In this analysis a significant interaction between 'conditions' and 'heights' was also found (*F*(3,15) =54.85, *p* =.015). This is interpeted as evidence that startle activity representative of different levels of arousal may also be involved during the voluntary preparatory phase indicating that subjects were more 'alert' in the preparatory landing task in specific circumstances.

Finally, it is concluded that cognition may play a more significant role than that previously assigned to it by proponents of the T visual strategy.

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DEDICATION

To my family:

specially to Mina,

and my parents

Ernesto and Margarita,

for their encouragement and support,

and to Tsily:

for her love and companionship.

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1. **Introduction**

The search for a theoretical framework in which the convergence of action and perception may take place is relatively new. In general, perception was regarded as an object of study unrelated to the environment and independent of the motor outcomes of the percepts. The origins of this tradition may date from the ancient atomistic approach on one hand, and from Plato's dualistic mind-body world on the other. In the process of research of sensory systems, the object of study (i.e., perception) has not carefully been investigated taking into account the reasons for perceiving, and the context in which it occurs. As noted by Johansson et al. (1980; p.388) "theories of perception have to a large extent been occupied with process and mechanism, ignoring why we perceive". In contrast, the Gestalt theory of Wertheimer, Koffka, and Køhler (as cited in Coren, Porac, and Ward, 1979, p.308), tended to focus on holistic phenomena, although movement was regarded as a means to study internal behavioral processes. J. J. Gibson (1950), influenced by this philosophy, advanced the concept of perception, action, and environment as a 'synergistic unit'. At the same time, the interest in movement per se as an area of study was mainly stimulated by the work of Bernstein (1984 d). Turvey (1974, 1977) in congruence with this trend, referred to an action / perception coalition. He incorporated in his views several elements provided by Gibson and Bernstein. Later, Kugler et al. (1980), and Kelso et al. (1980, 1981) extensively elaborated this dynamic view with an emphasis on the development of a new Action Theory.

This paper attempts to explore the perception of environmental information which is assumed to occur without the intervention of processing mediators. This information affords adaptive actions. It is perceived by means of those features of the environment that remain invariant under transformations. The free-fall task presented in the experiment is occasionally observed in real life situations of human and animal subjects. The following analysis is expected to lead to understand further the mechanisms by which visual information is incorporated in landing related tasks in the process of dissipation of vertical ground reaction forces after collision with the ground, in order to reduce injury risks to body structures.

2. **Literature Review**

2.1. The free-fall task as an object of investigation.

Initial studies on the reaction to vertical motion were done in children by Schaltenbrand in 1925 (as cited by Greenwood and Hopkins, 1980, p.295). Sudden transitions in acceleration caused a reflexive limb extension in babies. Gurnee (1934), in the same vein, conducted a study, the purpose of which was to investigate thresholds of response during upward and downward movements while subjects were blindfolded. The task consisted of pressing down a key with a finger on the right side hand when the subject detected that the movement was downward, and to press a second key on the left side when the movement was perceived as being upwards. The results of this rudimentary experimental design were interpreted as evidence that sensitivity to downward movements was greater. The early interest on reactions to falls were followed up several decades by Matthews (1956), Matthews and Whiteside (1960) and others, in more sophisticated and concise manner. These investigators hypothesized about the reflexive reactions of human subjects during sudden transitions from 0 g to 1 g in the vertical direction, i.e. from being supported to being in free-fall. Similarly, Melvill Jones and Watt (1971b) studied the latencies of onset of muscle electrical activity (EMG) related to the vestibular structures during unexpected falls. They mainly focused their research initiative on the otolith organs and their role in eliciting the observed EMG patterns. They adopted a design in which subjects were suddenly dropped while gripping a suspended bar with their hands. The release was obtained by means of an experimentally controlled electromagnetic mechanism. Their findings provided initial evidence on the role of long-latency reflexive responses acting during brief falls (2.5-20.3 cm height). They also mentioned that monosynaptic reflexes had no useful contribution in the landing response. However, Greenwood and Hopkins (1977) later reported that facilitation of the Hoffman reflex, which began at a latency of 30-40 msec after release, may represent the onset of motor neuron facilitation occurring before the onset of the EMG activity initially identified by Melvill Jones and Watt (1971a, b). This stereotyped EMG pattern observed in the gastrocnemius muscle was obtained at a mean latency of 74.2 msec after release. It was labeled by Melvill Jones and Watt (1971a, b) as a 'functional stretch reflex' (FSR) of otolith-spinal origin. They also acknowledged the similarity between the FSR and the 'long-loop' reflexes found by Eccles in 1966 (mentioned in Melvill Jones and Watt 1971a), envisaged by Phillips as a 'transcortical reflex' (cited in Kandel and Schwartz, 1985, p.492), and later studied at length by Fetz et al. (1980), Evarts (1985), and others. These findings during free-fall drops, stepping and hopping (Melvill Jones and Watt, 1971a, b), led to the conclusion that a pre-programmed neural message was activated and completed prior to contact with the ground, i.e., before the voluntary muscular response could become effective in the deceleration of the body mass. Therefore, the activation of the antigravity muscles in the lower limbs appeared to be independent of height of the fall, although, as noted by Melvill Jones and Watt "falls requiring less than 102 msec (5.1 cm) do not allow sufficient time for the build-up of any tension..." (1971b, p.735). In a preliminary report, Greenwood and Hopkins (1974) suggested that this initial burst, starting in the gastrocnemius muscle after approximately 75 msec, is primarily a response to release rather than to landing. In subsequent experiments, Greenwood and Hopkins (1976a) confirmed that the initial burst may be the consequence of a startle reflex to sudden release with coincidental contribution to deceleration of the body mass in unexpected landings from falls that last longer than 200 msec.

2.2. The effects of changes in acceleration on the initial peak of EMG activity.

Greenwood and Hopkins (1976a) designed an experiment in which the falling acceleration was controlled by counterbalancing weights while the subjects were suspended in a parachute harness. Their findings showed that accelerations lower than 1 g enhanced activity in the soleus muscle at a latency of 80 msec after release. The amplitude and the latency of the initial response remained unchanged for unexpected falls lasting up to 520 msec at gravitational acceleration, whether subjects were in blindfold or visual conditions. With regard to the effects of reduced accelerations on the peaks of activity, Greenwood and Hopkins (1976a) found that the timing of onset of the initial peak was unchanged until a certain point. At reduced acceleration ($< 2.0\ m \cdot s^{-2}$), this startle response was never apparent. Nevertheless, at acceleration magnitudes lower than gravitational, but higher than $2.0\ m \cdot s^{-2}$, the timing of the peak was unchanged but the amplitude was proportional to the acceleration during the fall. Significantly, if subjects voluntarily released themselves, the early burst of EMG activity was inhibited in all recorded flexor and extensor muscles of the upper and lower body, as well as in the periocular ones, regardless of the acceleration or the height of the fall, i.e., higher centers were hypothesized to take over the reflexive response (Greenwood and Hopkins, 1976a).

2.3. Evidence for dependence on the otolith organs.

The dependence on the otolith structures was confirmed by recordings in labyrinthectomized cats (Watt, 1976; 1981a; 1981b) which did not show this initial long-latency reflexive activity. The fact that neither subjects with absent labyrinthine function showed any startle reflexive responses during sudden drops (Greenwood and Hopkins, 1976a), supported Melvill Jones and Watt's suggestion (1971b) on its dependence primarily on the vestibular system.

2.4. Additional findings on the initial EMG burst in landing-related experiments.

The first burst was also elicited in monkeys during unexpected drops of 90 cm height (Lacour et al., 1978; Vidal et al., 1979), while in humans this vestibulo (otolith)-spinal reflex was also observed during normal locomotion (Melvill Jones et al., 1973), running (Melvill Jones, 1973), hopping (Melvill Jones and Watt, 1971a), and during downward steps (Melvill Jones and Watt, 1971a; Greenwood and Hopkins, 1976b), or during falls after prolonged weightlessness conditions (Watt et al., 1986). This response to release, nevertheless, was generally present within a consistent time period. Greenwood and Hopkins (1976b) found that for unexpected falls lasting long enough, the initial peak was over by about 220 msec after release, followed by a period of relative silence that concluded with the initiation of a second burst of EMG activity prior to landing. Figure 1 shows a typical EMG pattern (adapted from Greenwood and Hopkins, 1976a).

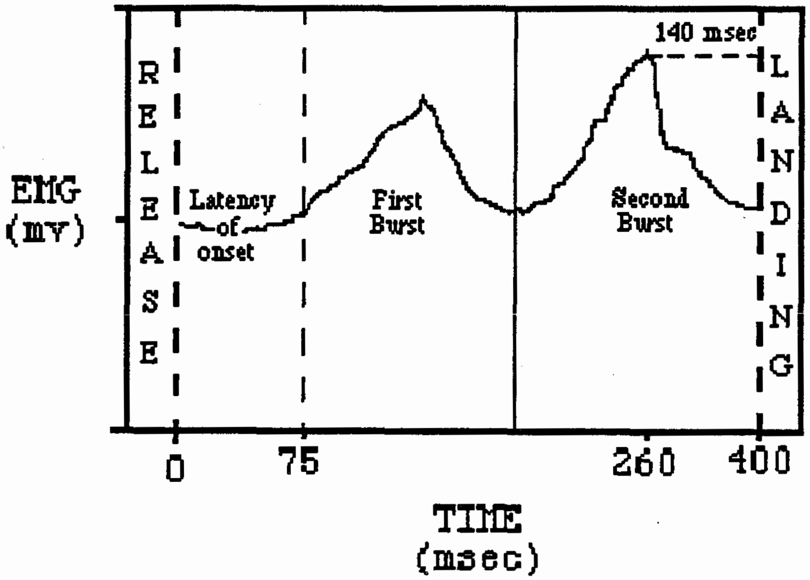


Figure 1 The first and second bursts of EMG activity in a landing related muscle during the flight path.

2.5. The voluntary response during landing related tasks.

Greenwood and Hopkins (1976a) noticed that the second peak was consistently observed if the unexpected falls were longer than 300 msec. They interpreted this pattern as being concerned with the voluntary muscle control **related to the moment of landing** (Greenwood and Hopkins, 1980, p.299). It seems, however, that this pattern could be rather attributed to the moment of release as in the case of the first burst, since blindfolded subjects could not see the landing surface, and thus could not determine the moment of touchdown.

Melvill Jones and Watt (1971b) mentioned as well that falls lasting longer than 102 msec (5.1 cm) allow a build-up of muscle tension, and after 195 msec the voluntary muscle response is seen as a second burst of EMG activity. In their investigation, Greenwood and Hopkins (1976a) experimentally controlled the duration of the fall by varying the height or the acceleration. Different heights of fall at constant acceleration delayed the onset of the second EMG peak, but did not seem to cause any change in the amplitude (the higher the fall the longer the silent period after the end of the first burst of EMG activity). On the other hand, different accelerations at constant height influenced both the amplitude and the onset latency of the second peak. Significantly, its maximum always appeared 40-140 msec prior to landing, in all subjects (normal or with absent labyrinthine function) in the relevant decelerative muscles (flexors and extensors of the knee and ankle joints), even at low accelerations (Greenwood and Hopkins, 1976a). Watt (1976) noticed the same response in cats, while Melvill Jones and Watt (1971a) reported this consistent timing in a hopping performance, and during a downward stepping motion. The latter was confirmed by Freedman et al. (1976) and Craik et al. (1982). In the same vein, Dietz and Noth (1978) observed an invariant timing in the latency of onset of the triceps brachii at 130-200 msec prior the collision with a landing board in a forward falling task. But as Craik et al. stated "the precise mechanism(s) responsible for its origin remain unresolved" (1982, p.400). With respect to this invariant 'time-window', Greenwood and Hopkins reported that it is "dependent on the acceleration or the height" (1976b, p.384), and also observed that the changes in timing and amplitude of the visual and blindfold conditions were "not very different" (1976b, p.381). In a somewhat analogous approach to that of Greenwood and Hopkins (1976b), Dietz and Noth (1978) reported that the timing of the triceps brachii pre-innervation in both visual conditions was also similar in forward falling motions initiated by the subjects. It is this observation that is further examined in the present investigation.

The common factor to all the conditions in these experimental situations is the time period allowed to the subjects for adjusting their response as soon as they perceived and evaluated the urgency of the situation. However, no reference was ever made to the time-to-collision with the ground, nor was an attempt made to interpret the consistent timing in the landing response in light of this temporal variable. It is worth noting that Greenwood and Hopkins provided substantial information, and partially confirmed and/or reinterpreted earlier findings. In contrast, later studies did not follow their initiative and devoted attention mainly to the initial long-latency reflexes, thus neglecting the voluntary phase represented by the late burst of EMG activity. In most of these investigations the conclusion was that the vestibular otolith structures are predominant in arousing the observed EMG pattern during falls. Considering, however, that the otolith organs alone are limited in their capacity to account for informative events in the space-time environmental coordinates, it seems very unlikely to find an explanation of the voluntary pattern in light of studies that focused merely on the vestibular correlates of the observed landing responses. Some studies reported findings that support the almost obvious involvement of the visual system in orientation of individuals with respect to the vertical plane of movement. Malcolm and

1973, p.128) also reported that blindfolded subjects sitting in an erect position were unable to make reliable movement estimates during vertical sinusoidal oscillations.

3. The 'ecological perspective' with reference to visual perception

3.1. The role of the visual system in the timing of the voluntary response.

At first glance, it may appear that vision is a more appropriate source to detect information about movement and direction of the body since it is 'exteroceptive'. Recognizing this fact, Vidal et al. (1979) experimented on monkeys, and provided evidence on the role of vision during free-falls. In conditions in which the animal's visual field was stabilized (with respect to the head) or in complete darkness, a significant decrease in muscular response was observed in both early and late EMG components of all extensor muscles compared to normal vision conditions. These and later findings in humans (Wicke and Oman, 1982), suggested that the visual system as well as the otolith organs may play a significant role in the observed actions during unexpected falls. This questioned the 'predominant' involvement of the vestibular system in the study of the landing reflexive responses. With respect to the voluntary phase (i.e, the second burst of EMG activity), it was usually regarded as "complex in nature" (Watt et al., 1986, p.308). The voluntary landing response seems to have been neglected as an topic of investigation within the current neurophysiological approaches, whether the visual or the vestibular systems were involved in these studies. The lack of theoretical context for the observed neurophysiological correlates of movement put these findings at a factual level, i.e., no further interpretations were possible with regard to movement organization and control. As expressed by Granit (1973, p.14) "if one merely persists in demonstrating that site a inhibits or excites site b, c, or d, neglecting teleological questions of what purpose all of it serves and how it responds to variations of 'demand', then, in the end one will be in possession of a body of knowledge, to be sure, but knowledge likely to become merely an amorphous conglomerate of well-documented facts".

3.2. The Direct Perception framework.

The difficulty in explaining the voluntary actions during sudden falls may be a consequence of the approach taken. One of the main assumptions made by supporters of the representational view is that the control of movement is an achievement of the nervous system, through processes undergoing inside the individual, irrespective of the environment in which the motor behavior is observed. As a result of this dichotomy, the landing response should be regarded as the result of the changes in magnitude of the vertical acceleration beyond a certain triggering threshold. In this internal process the mechanical input is transduced into electrical activity. Highly sensitive receptors deliver neural messages of different frequencies and amplitudes to hierarchically organized functional-anatomical structures. These are assumed to be responsible for the processing of relevant variables within the nervous system. As such, the brain (i.e., the highest element of the hierarchy) acquires knowledge, it memorizes and learns in order to give an appropriate response in similar future events. From this perspective the 'computing organism' is dissociated from the changing surroundings, and the command for a pre-programmed action occurs as a consequence of the integration of triggering stimuli provided by a 'non-informative' environment. Subsequently, mental representations of environmental constraints and movement patterns are achieved by the brain computational abilities (see Ullman, 1980, for an extensive discussion on the computational-representational view in contrast to the direct perception approach). However, this line of thought did not seem to satisfactorily reach an answer to some main questions of movement research; e.g., how does coordinated action occur in response to unlimited varieties of unique environmental events and in the presence of the large numbers of internal degrees of freedom existing in a multi-link body system; or what is the role of perception / action, and what is the link between them.

In an ecosystem, in which an animal-environment synergy is assumed, the brain 'does' things rather than 'has' them inside, i.e., knows, it perceives, and experiences (Michaels and Carello, 1981). With regard to event-perception, this approach known as 'dynamic' or 'direct', postulates that perceptual systems detect without mediators, information which is already in the environment as structured energy. This ecological approach regards the environment, the perceptuo-motor system, and the brain as a coalition. Gibson expressed this relationship within his 'ecological optics' views stating that "... natural vision depends on the eyes in the head on a body supported by the ground, the brain being only the central organ of a complete visual system." (Gibson, 1979, p.1). Thus, within this theory, the brain need not be fully concerned with computation or integration of sensory input, since the environment is rich in directly perceivable information which affords appropriate adaptive actions (changes in the relationship between energy distributions). Turvey and Kugler, in accordance with the direct perception approach, mentioned that "an action is what it is by virtue of its intentions, that is, the motor problem (a needed change in the relation of the animal and its environment) toward which action is directed as a solution" (1984, p.373).

Subsequently, it is of critical relevance to devote attention to the study of those features of the environmental stimuli that originate immediate perception without going into 'cognitive computations' for each single occurring event. These features seem to be some properties of the tri-dimensional environment which remain unaltered in a bi-dimensional projection along transformations at the optic array due to relative motion with respect to the observer's eyes (Reed and Jones, 1982). As manifested by supporters of the ecological approach, this is a process in which 'knowing' becomes relevant rather than 'having knowledge', i.e., perception is the act of knowing the environment, while action is the act of changing the relationship between organism.and environment in time and space when the information obtained through exploring it (i.e., perceiving) affords such a change. Animal and environment interact by means of energy flows tending to an equilibrium point (i.e., they are in a non-equilibrium state), whereas "intentional objects are lawfully specified by structured energy distributions" (Turvey et al., 1981; as cited by Turvey and Kugler, 1984, p.398). Ever-changing environmental conditions lead to adaptive actions in search for a <u>dynamic equilibrium</u>. Thus, action as one element of the continuum may <u>not</u> be the result of a set of stimulating agents which enhance 'a priori' movement representations and trigger motor programs as a response. Action could be rather regarded as the result of the constraints and the dynamical laws ruling the system, that give rise as 'a posteriori' facts, to self-regulatory properties of processes (linear and non-linear) involved in coordinative actions of open biological systems (i.e., systems that exchange matter and energy with the surroundings), as supported by Kelso et al. (1980, 1981), Kugler, et al. (1980), and others. This view is complementary with Bernstein's (1984d) insights on the control of large number of degrees of freedom, the relation between perceiving accurately objective environmental facts and goal-directed movements, and the prospective regulation of action. From this perspective, the role of the brain, as much as that of the visual or other systems during free-falls, is to detect better the high-order properties of the environment specified in the form of informational 'invariants', in accordance with Gibson (1950, 1966, 1979). For example, a change in the relative position of objects during a free-fall (a flow of the optical stimulation), affords information about the environmental surfaces and information about the movement of the observer relative to that environment, giving rise to a preventive muscular action with the necessary power output at the right time before contacting the ground (for a brief review of the Direct Perception approach, see Michaels and Carello, 1981).

3.3. The time-to-contact variable.

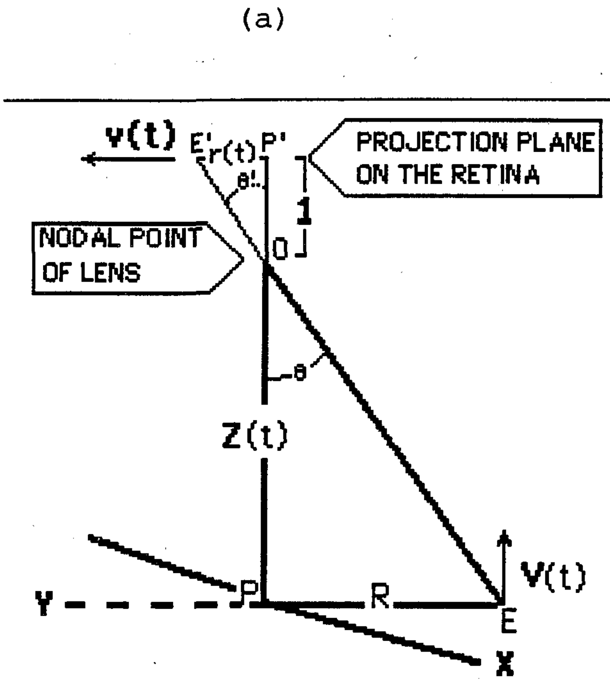
Gibson's 'ecological approach' provided an alternative to the traditional views. Based on these principles, Lee (1974, 1976, 1980a, b) and Lee et al. (1983) presented a substantial basis of support for the idea that the optically specified time-to-contact with the ground may play an important informative role in the voluntary control of landing. These studies included the essential information to interpret the voluntary response during free-falls as a function of the available information at the optic array. Lee (1976) even cited jumping down from a height as an example in which the individual can visually pick up the time-to-contact with the ground in order to initiate a preparatory muscle action for absorbing the impact with the landing surface. This time-related variable is perceived by the falling subject as he moves through the environment, i.e., "the optic array at his eyes changes continuously, giving rise to an optical flow pattern" (Lee, 1974, p.250), which specifies the necessary kinesthetic information about the temporal and spatial relations between objects and the observer's movement. Movement is perceived 'exterospecifically' through vision (Gibson, 1979), and kinesthetically activated mainly through the otolith organs at the initiation of the fall by the change in acceleration from 1 g to 0 g (Greenwood and

Hopkins, 1976a, b; Melvill Jones and Watt, 1971b; Watt, 1976, 1981a, b). The velocity and the position vectors at the optic array define the identity of the optic elements in the optic velocity field (Lee, 1974). Acceleration relates to the change in velocity of the optic element. The optically specified velocity variable at a specific point in the time-space coordinates depends on the initial height of fall. Lee defined the optic velocity field as: "the set of velocities of optic elements past positions on the cylindrical optic projection surface" (1974, p.253). During the performance of a free-fall task, the inverse of the rate of dilation of the landing surface at the optic array specifies an optic time-dependent variable "tau" (τ). Lee et al. (1983) mentioned that $\tau_{(t)}$ is equal to the time-to-contact when the approaching velocity is constant.

3.4. The τ heuristic and the timing of the landing response.

Lee (in von Hofsten and Lee, 1985) suggested the idea that the $\tau_{(t)}$ invariant may include the information needed to adopt a landing strategy based on the time-to-contact, without going through mental computations over other detected variables (e.g., height, velocity, and acceleration). Todd (1981) presented an analysis that allows one to follow the rationale behind the concept that information is directly available at the optic array. Visual information about velocity and acceleration does not seem to be useful, as suggested by Todd. These variables are available and essential for performing the task, but subjects are unable to take advantage of them. Rather the time-to-contact may seem to be a more efficient alternative. Todd (1981) in his experiments showed that individuals are sensitive to this type of information at the optic array. Using computerized simulations about moving objects, he concluded that "the observers made accurate judgments about relative time to collision based on a ratio between an object's projected size and its rate of expansion". He then went on to mention that "... some potentially informative relationships among optic variables, (...), cannot be exploited by human observers." (1981, p.807,). It does not seem to be necessary either to obtain a three-dimensional visual image of the environment in order to perceive time-to-contact. Schiff and Detwiler (1979) investigated whether three-dimensional and two-dimensional forms of optic information are used by subjects to anticipate impending collisions. Their findings supported the view that "two-dimensional rate of angular-size-change invariants mediate judgments of collision time" (1979, p.656).

In the free-fall task used in this experiment, the optic elements are assumed, for convinience, to be in parallel with the direction of the fall and perpendicular to the ground as shown in the next figures, based on Lee and Reddish (1981).



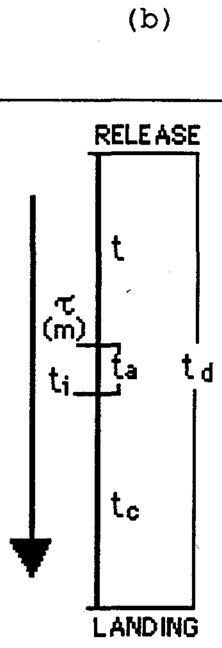


Figure 2a The point of observation of an individual suspended from an overhead bar with respect to a flat landing surface.

Figure 2b The optically specified variables along the flight path of a falling observer.

Where for Figure 2a:

V(t) = velocity of O in the direction Z at time t.

OXYZ = moving reference plane define by the Cartesian coordinates with respect to the ground or fixed environmental frames of reference on the retina, where Y defines the saggittal plane.

O = defines the center of the hemispheric retina of the eye at position Z and time t.

E = is the relative position at time t of an arbitrary environmental texture element (or an optically differentiable unit).

R = the distance from a random environmental point E to the point P of the surface on the Z vertical axis.

Z = the distance of the observer's eyes from the center of the optic field on the moving direction at time t.

E'= the optic image of E at time t along the longitude and latitude coordinates relative to the landing pole P' (as defined by O and P, which may be treated as distances on the optic projection surface).

Ø = is the angle defined by points E O P.

Ø' = is the angle defined by points E'O P' at the optic array.

P' = the landing pole, i.e., the optic image of the surface element to which the eye is heading (towards the landing surface).

1 = is the distance from O to P', from the center of

the lens to the retina in the eye of the observer, considered as a constant unit.

For Figure 2b:

t_d = the total flight time.

t = is the period of time which elapses from the initiation of the fall until the individual perceives that $\tau_{(t)}$ has reached its critical value.

t_a = time delay between perception of tau(m) and the initiation of the activity in the preparatory landing muscles.

t_i = the moment of initiation of the muscular activity.

t_c = the time-to-contact as perceived by the individual when tau reached a critical value.

$\tau_{(m)}$= the critical value of $\tau_{(t)}$ resulting from an ongoing series of ratios between the distance from the landing surface , and the velocity V(f) at different points of the flight path (assumed by the falling observer to be constant).

The information about time-to-contact with the ground may explain the pattern of EMG activity observed in the landing related muscles before landing. Lee and Thomson, in a study mentioned that in an approach to a surface the optic variable τ "specifies the time-to-contact, which is the type of information that a bird needs in preparing to land" (1982, p.420). The equations shown in the next section allow the computation of the τ variable, in accordance with Lee (1976, 1980a, b), Lee and Reddish (1981), and Lee et al. (1983).

3.5. The $\tau_{(t)}$ computation.

The distance coordinates Z(t) and R, together with the angle between the planes E O P and E'O P' define the position of any optic element E relative to the eye of the observer. This angle is specified at the optic array by the angular coordinate $\emptyset'$ of the optic element E'. Z(t) and R are specified by similar triangles, as expressed in the following equation:

$$(1) \qquad Z(t) / R = 1 / r(t)$$

Assuming that the eyes of the falling subject are at time t at height Z(t), while he is moving vertically towards the landing surface with a velocity V(t), then the time-to-contact is specified in the optic flow field by differentiating equation (1) with respect to time, which results in:

$$(2) \qquad Z / V = r(t) / v = \tau_{(t)}$$

The τ value equals the time-to-contact at constant closing velocity specified by $\tau_{(t)}$ (for differentiation procedures see appendix A). Nevertheless, the falling subject approaches the landing surface with acceleration, rather than at constant velocity. Assuming that the initial velocity is $V(0) = 0$, the initial height of the fall is $Z(0)$, and having a constant gravitational acceleration $A = 9.81$ m/sec^2, then we may determine the height $Z(t)$ and the velocity $V(t)$ at any point t of the time coordinate where:

$$Z(t) = [Z(0) - (A \cdot t^2 / 2) \; ; \text{ and } V(t) = A \cdot t.$$

Then the optical parameter $\tau_{(t)} = Z(t) / V(t)$ (the time derivative which specifies the time-to-contact) will be :

$$(3) \qquad \tau_{(t)} = (t_d^2 - t^2) / 2 \cdot t \; ;$$

whereas the total flight duration is
$t_d = (2 \cdot Z(0) / A)^{1/2}$.
Then the time-to-contact $t_c = t_d - t$, or:

$$(4) \qquad t_c = \tau_{(t)} + t_d - [\tau_{(t)}{}^2 + t_d{}^2]^{1/2}$$

When the movement is accelerated, as in the case of the diving gannets, the τ optical variable does not specify the time-to-contact (Lee and Reddish, 1981). In such conditions

$\tau_{(t)}$ may constitute the basis for the strategy used to time the streamlining performance of their wings (Lee and Reddish, 1981). Thus, in light of the urgency of the situation in the landing task, it seems plausible that individuals start the voluntary action during the flight path when the optic variable τ reaches a margin value $\tau_{(m)}$ at which the preparatory action must take place. The time-margin value (i.e., t_m) is specified by the difference between the total time of flight t_d (calculated from the Newtonian formulae), and the time-to-contact. The heuristic may be conceptualized as follows:

Assuming that the falling subject starts his action after he detected that $\tau_{(t)}$ has reached a margin value $\tau_{(m)}$, and considering that there is a delay t_a between perception and action, then $t + t_a = t_m$, and the time-to-contact t_c is:

$$t_c = \tau_{(m)} + t_d - [\tau_{(m)}^2 + t_d^2]^{1/2} - t_a \tag{5}$$

3.6. Evidence for the use of the τ strategy in animal and human subjects.

Lee (in von Hofsten and Lee, 1985, p.237) mentioned that the gannets in Lee and Reddish's study (1981) "might have found adequate to essentially ignore acceleration and visually time their actions as if they were traveling at constant speed, (...) they might be using a simple 'τ

strategy', starting to streamline their bodies for entry when τ reached a critical value". Similarly, Wehrhahn et al. (1981) presented evidence showing that stimulation originating in the optic flow field by different experimentally induced motions on two planes, elicited the landing response in houseflies when a critical value was reached. Wagner (1982) showed that information contained in the optical flow field triggers the pre-landing deceleration and leg extension of houseflies. Wagner suggested that time, not distance, is the important cue. Lee (1976) also showed that drivers seem to use the $\tau_{(m)}$ heuristic in adjusting their braking response when confronted with static or moving objects on the collision course. Similarly, practical implications of this concepts have been reported in training children in road crossing when approaching cars were estimated to be within the time range of collision with the individuals (Lee et al., 1984). In athletic performances, Lee et al. (1982) mentioned that in the adjustment of the run-up to the take-off board in long jumping, subjects directly perceived the time-to-contact through the optic variable τ. Hay (1988) confirmed some of these findings in a larger sample of elite athletes of both sexes. In running over irregular terrains, it has been shown that individuals visually control their step length following this time-based model. The vertical component of the running steps seems to be regulated by the optic variable τ (Warren et al., 1986). Adults seem to time the take-off moment in ski-jumping performances guided by the same principles (Lee and Young, 1985; 1986). Lee et al. (1984) cited a case in which information of visual origin is used by hemiplegic patients after a cerebro-vascular stroke, guided by the same principles. In other experiment, Lee et al. (1983) intended to determine the extent to which healthy subjects adopted the τ strategy in timing the response in hitting an accelerating ball. The angular changes of the knee and elbow joints indicate that subjects respond when $\tau_{(t)}$ reaches the critical value $\tau_{(m)}$. Lee mentions (in von Hofsten and Lee, 1985, p. 238) that the design used in the latter case substituted the landing task because it made possible to obtain longer times to contact which are not likely to be obtained in free-falls for safety reasons. It is worth noting that Lee et al. (1983) reported that for $\tau_{(m)} < 250$ msec the time-to-contact t_c equals $\tau_{(t)}$, in spite of the acceleration and irrespective of the height of the fall. That is, a linear trend was evident.

3.7. <u>The time-to-contact information related to dissipation of ground reaction forces</u>.

In the context of a dynamic view of perception, the information about events is determined by the intention of the act. The motives or goals of an animal in its specific environment will enhance perception of information which affords the fulfillment of the motives. In the landing task, the goal is primarily the dissipation of vertical ground reaction forces to avoid injuries at contact with a surface which affords 'collision' by its specific characteristics. The intention will thus have an influence in the dynamics of the action as well. Herein lies the relevance of the perceptual information in relation to action. Secondly, the individual must adjust the action through optimal timing and appropriate muscular power in order to dissipate the forces acting upon the body after touchdown the best the individual can. The information necessary is both extrinsically and intrinsically defined to the individual. The former refers to height of fall, and its first and second order time derivatives. They are specified at the optic flow field by the scale-independent variable τ. The intrinsic source of information, however, is assumed to be system-scaled in meaningful body units. For example, limb proportion with respect to the height of fall (Turvey and Carello, 1986), or to the height of climbing step (Warren, 1984; Mark and Vogele, 1987), the height of a sitting chair (Mark and Vogele, 1987), the height of the observer's eyes from the walking surface (Lee, 1974), and body mass - power ratio to dissipate the momentum gained at contact with the ground (Warren and Kelso, 1985). Extrinsic information, therefore, is meaningless in absolute units of distance, velocity, and acceleration, and without the intrinsic sources, the individual will not be able to organize the intentional action. Lee and Thomson mentioned that exproprioceptive, 'body-scaled', information about the environment is relevant in controlling activity. They considered the exproprioceptive information as "essential for timing actions relative to the environment" (1982, p.420). Exproprioceptive cues are regarded as a "union of exteroceptive and proprioceptive information, namely information about the position, orientation, and movement of the body or part of the body relative to the environment" (Lee, 1980a, p.282). The landing reaction should be a function of the height of the fall, and the body's relation to that specific height.

How can an individual determine its body mass to power ratio, and how can this be applied to adjust the dissipative power relative to the height of fall? This is done, according to some, by 'exploratory processes' (as expressed by Michaels and Carello, 1981) in which the perceptual systems become 'tuned' or 'resonate' better (Gibson, 1979) to the extrinsic and intrinsic information. The actor may become perceptually better in the immediate pickup of the time-to-contact information, and in the adjustments of muscular output relative to his body weight necessary to avoid injuries.

The question of "how perception guides action, and how action constrains perception rests on the understanding of how power and information are mutually linked" (Warren and Kelso, 1985, p.274). It is worth remarking that information within Gibson's ecological framework, is 'determinate', and it refers "to macroscopic patterning of lower-energy fields (e.g., optical, acoustical, chemical, etc.) that are generated lawfully by higher-energy fields (e.g., the layout of potentials and reflective surfaces) and by the displacements of living systems relative to these fields" (Kugler and Turvey, 1987, p. 9).

4. The purpose of the present study

In the present experiment the time-of-initiation of the activity (in muscles relevant to the preparation for landing) and the flight time (dependent on the height of fall) were hypothesized to be related in a consistent manner. The use of the $\tau_{(m)}$ strategy was assessed within the "Direct Perception" conceptual framework. Accordingly, the performer is thought to directly pick up the information about the time-to-contact by means of the τ heuristic based on optically specified variables available to the individual when moving through the environment. A time delay t_a between the $\tau_{(m)}$ value and time of initiation of the action t_i (the latency of the EMG peak) was expected. This time gap may be attributed to a characteristic visuo-motor delay required by the information on the retina to give rise to the neural message and to elicit the action of the motor system, i.e., the perception-to-action time. Lee and Reddish (1981) in their study found that on plummeting gannets (using cinematographic techniques) the period from the hypothetical optical variable specifying time of initiation until the birds started streamlining their wings was approximately 60 msec. In humans, Lee et al. (1983) found a delay within the range of 50-135 msec while subjects performed a hitting-a-dropping ball task, measured at the initiation of changes in the knee and elbow joint angles.

Performers falling from different heights will achieve different final velocities V(f): the higher the initial height (Z(0)) the greater the final velocity V(f) at constant gravitational acceleration. Hence, the higher the fall, the earlier in space during the flight path the performer should start to react, and hence diminish the risks of injury by the timing the response before the landing. With increases in the height of fall the time-to-contact (i.e., the time for effective preparatory action during the flight path) was expected to increase following a negatively accelerated relationship (i.e., an exponential saturated curve approaching an asymptote with increases in the height of fall).

4.1. Hypotheses.

The major hypotheses in this study were:

a) The time-to-contact will be 'directly' perceived in vision conditions. The relationship between visual stimulation and the observers' movement with respect to the environment is expected to follow the optical τ heuristic.

b) Increasing the height of the fall in both vision and no-vision conditions will differentially affect the onset of the preparatory EMG activity in the relevant landing muscles.

c) In no-vision conditions subjects will not rely on the same protective strategies as when visual cues are allowed. It is hypothesized that the strategy used when vision is occluded will be represented by a linear relationship between the time left until touchdown (perceived time-to-contact measured from the moment of initiation of the EMG activity), and the total flight time, which delimits the time for effective action.

d) The strategy adopted by the falling performers in vision, compared to no-vision conditions, will enhance the ability to dissipate the vertical ground reaction forces during the landing (as measured by Peak Forces, and Time to Peak Forces).

4.2. Assumptions.

Two assumptions with respect to this study were made:

a) Facilitation of an effective action is expected to be enhanced by the pick up of information affording 'landing' via the 'perceptual systems'. In this case, the latter were assumed to be a combination of stimulation of the visual system (providing information about changes at the optic array), together with information from the vestibular structures (kinesthetic information about changes in acceleration and head position), and proprioceptive information about changes in pressure exerted on the soft structures of the falling body, all of which are assumed to co-act (Johansson, 1973).

b) It was assumed as well that angular changes at the retina of the eye occur by both, a flow of information at the optic array, and by changes of the eyeball in its orbit (after Johansson, 1973). Both are used by the observer to gather information. However, the object of study in this paper relates to the former, since it is assumed to be relevant for the pickup of information about time-to-contact.

5. **Methods**

5.1. Subjects.

Six male subjects (mean age = 26.16 years; range = 22-32 years) completed the tests in two different sessions. All were randomly selected from an injury-free student population from Simon Fraser University. Their mean height was 177.83 cm (range = 173-184 cm), and their mean body mass was 76.66 kg (range = 67-88 kg). After signing the required consent forms they were randomly assigned to one of the two starting conditions (blindfold or vision). A time schedule was pre-arranged for each participant with a rest period between the two sessions (2-4 days). Subjects were paid for their partial or complete participation.

5.2. Apparatus.

A free-fall device was designed for the experiment. The apparatus comprised a steel overhead bar which was oriented horizontally and could be set at a variety of heights from the floor. An electromagnetic-sensitive switch interfaced to the computer via an A / D converter was attached to the steel bar. Six pairs of Beckman surface electrodes were applied on the subjects' left leg and forehead to measure muscle electrical activity. The signals were amplified by a custom made EMG amplifier (gain 10-1000) which allowed simultaneous recording from 8 channels. Signals could also be integrated, enveloped, or band-pass filtered. A ground lead, 1 cm wide and 5 m long was used to diminish noise while attached to the subjects waist. An oscilloscope allowed calibration of the devices, and also served as a continuous feedback source from selected EMG channels during the recording process. Failures in EMG signal gathering could be anticipated by its use during the practice trials. Prior to the start of the experiment a Hewlett-Packard 3310A function generator was installed at a frequency of 11000 Hz (11 channels going into the A / D converter), calibrated by a Systron Donner 7034 frequency counter unit within a precision of ±1 Hz. The frequency generator served as an external clock that determined the sampling rate from the analogue sources.

Subjects landed upon a Kistler force platform (model 9261A) connected to suitable charge amplifiers (Kaig 5001) which allowed measurement of vertical ground reaction forces. The force plate was covered with a 1/4 inch dense rubber foam to minimize pain caused by landing barefooted on the metallic surface. All devices were appropriately grounded. In the no-vision conditions subjects used a pair of adjustable (swimming type) dark goggles. The performers were suspended from the steel bar by gripping it with their hands. The trials started upon release of a mechanical lever which supported a magnet.

The signal gathering process comprised analogue and digital signals simultaneously obtained. The analogue recordings were done on-line in a Hioki 8801 chart-recorder (4 channels)[1], and saved on tape using a Precision Instruments FM recorder PI-6200 (5 channels, at speed =3.75 in/sec). EMG and force plate outputs were conditioned by pre-amplifiers, and sampled via an A / D converter (LabPack). An IBM-PC microcomputer controlled the data gathering and storage processes a custom software program (developed in "C" programming language)[2]. Raw signals (binary files) were plotted during the experimental trials on an IBM-XT microcomputer by using a modified "Plotter" program (written in "Turbo-Pascal" language). This allowed a continuous inspection of the data collected during the ongoing experiment. The off-line data analysis was done on an IBM-AT microcomputer by using the original version of the "Plotter" program written in "Turbo-Pascal" for files converted to 'Ascii format'[3]. The required dependent variables were then obtained (onset of EMG activity in 6 muscles, time of release, time of touchdown, peak forces, and times to peak). The analysis of the data was done on a Macintosh SE

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[1] Appoximately 10% of the trials were recorded on the chart-recorder due to malfunctioning of the FM device.

[2] A listing of the program is available by contacting R. Taylor, School of Kinesiology, Simon Fraser University, Burnaby, B.C., V5A 1S6, Canada.

[3] A listing of the program is available by contacting P. Nagelkerke, School of Kinesiology, Simon Fraser University, Burnaby, B.C., V5A 1S6, Canada.

microcomputer for which statistical, graphics, and spreadsheet application programs were available (MacSS and StatView, CricketGraph, and Microsoft Excel, respectively). Best-fitting curves were calculated by using a computer program on an Apple II computer ("Microcomputer Based Models in Biology", by Spain, 1982). This particular software incorporated the exponential saturation model and provided a complete statistical output of the regression process, including the residuals' values and the best-fitting curve values that were later plotted in a graphic application in order to be carefully inspected.

5.3. Procedures.

Subjects were provided with initial instructions on the task and the procedures of the experiment. An explanation sheet, a consent form, and a health related questionnaire were given to those participants that fulfilled the initial requirements (i.e., neurological and back symptom-free individuals). Appendix B and C present the written instructions and the questionnaire provided to the subjects before initiation of the sessions. Warm-up and practice trials then followed. The technique of landing was improved during this practice period by providing verbal feedback. Individuals were instructed to use the joints, but to prevent sudden deep flexions of the knees. They were told to perform almost "noiseless" landings, bearing in mind that the task involved a certain degree of injury risks. EMG electrodes were applied over six muscle groups following standard preparation procedures. Muscles were located according to the instructions provided in the electromyography literature (Delagi et al., 1975). The muscle groups of interest were: gastrocnemius (medial head), tibialis anterior, vastus lateralis, biceps femoris (lateral head), rectus femoris, and the frontalis muscle (2 cm laterally from the midline of the forehead, 1 cm above the eyebrow), all on the left half of the body. The ground lead consisted of a 5 m long wire, surrounded with gauze straps moistened with a salty solution. It was attached to the subjects waist in a belt-like manner. This proved to be the most efficient way to reduce artifact and interference noise in the recorded EMG signals. All subjects performed 10 trials (the first four were considered as a part of the practice trials) at each of four heights of fall in a semi-counterbalanced order (4 heights over 6 subjects did not allow for full counterbalanced order). The landings took place onto the force platform within a limited rectangular surface of 40 cm x 60 cm, covered with a dense red rubber foam (1/4 inch thick) that made the landing area distinguishable from the floor. All subjects were barefooted throughout the landing trials. In 'no-vision' conditions subjects were allowed to know the falling height, and they could see the landing surface until the goggles were applied, just before the initiation of the respective landing trial. An overall equipment test followed. The overhead bar was pre-adjusted at the appropriate height of fall while the individual performed the practice trials (often not more than 3 consecutive landings without the recording devices and 4 with the complete set-up). The performers started the experiment when they indicated that they were ready. By climbing a ladder located beside the landing device, the subjects approached the overhead bar and then pressed the mechanical lever that brought the magnet to an electromagnetic sensitive cell inactivating the recording system. Upon release, the switch opened an inverted circuit that caused a drop in voltage read by the computer as the initiation of the fall. Subjects were instructed to relax and to release themselves by suddenly opening their hands in order to perform a vertical landing. Lateral and antero-posterior swings were eliminated by steadying the performer's legs and waist prior release. During vision conditions the subjects were instructed to fixate their glance on a reference band-width delimited by two lines 30-50 cm apart from the landing platform. The task and the apparatus are illustrated in Figures 3a , b, and c.

Figure 3a The landing task (side view) and the free-fall device.

Figure 3b The landing task (front view) and the free-fall device.

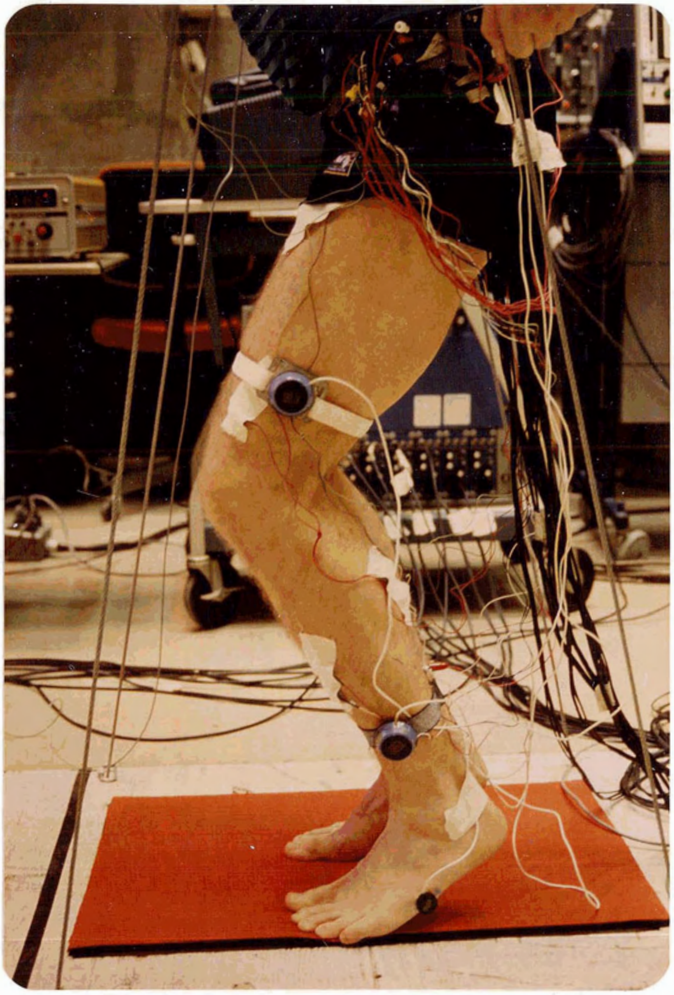

Figure 3c EMG and Goniometer applications on the left leg of the performer.

All analogue signals (from EMG and force platform) were sampled at a frequency of 1000 Hz. Data recording took place throughout a period of 2.5 sec distributed over three different phases of the task: 1.5 sec prior to release, 1 sec after release of the switch which allowed recordings during the flight (approx. ≤ 430 msec), and after touchdown (approx. ≥ 570 msec). The data gathering program was set at a gain which would read signals within ± 1.25 volts range. The EMG recordings were amplified 1000 times. The force plate gain was set at 5000 mechanical units / volt , which was assumed to be satisfactory for collecting force magnitudes elicited by an 85 kg falling body from 1 m height at gravitational acceleration, and within the computer pre-set gain. Analogue recordings from 5 channels were also obtained on-line from an FM-recorder throughout most of the sessions, whereas in a few cases they were obtained from an HIOKI chart-recorder. Analogue and digital signals were then compared in order to verify if any time delays occurred during the signal conversion process done by the computer.

Subjects received limited knowledge of performance ('not so good', 'good', and 'excellent' landing). This was based on a rather subjective evaluation done by the experimenter which took into account characteristics such as smoothness of the landing, symmetry during the flight and after landing, non-rigid joints, stability after touchdown. However, subjects were also left to their own perception of the landing performance and were often asked about how the landing felt.

5.4. Design.

The six subjects performed 6 blocked landings from each of the 5-10, 20-25, 60-65, and 90-95 cm heights (in counterbalanced order), resulting in 24 trials for vision and 24 trials for no-vision conditions in two different days (i.e., total trials = 48). The analysis was based on six 'completed trials' (trials in which no recording failures were detected). Four practice trials with a complete experimental setup were previously performed in each landing category.

5.5. Analysis.

The onset of EMG activity in the different muscles was obtained from plottings of the raw data on an IBM AT microcomputer using a plotter application especially written for this purpose. The plotter program visualized on the screen signals of 3 different muscles simultaneously, with a resolution of 80 lines per muscle plotted (40 lines in each direction of the baseline). The difference between each line represented a range of 15.625 mv in either direction. The digitized values for each data point were simultaneously seen on the screen, and the onset of muscular activity could be determined by highlighting the plot with a cursor key that controlled a dot of different color. In appendix D a typical trial is shown from which the dependent variables could be obtained. The method used took in to account a baseline within a period of relative relaxation (i.e., the EMG signals 1.5 sec before release while the subject remain suspended from the overhead bar). The EMG bursts surpassing this values over periods of time of at least 10 msec were considered to represent significant activity. To determine a typical EMG burst for the specific muscle and subject, samples of individual signals were examined prior to obtaining the dependent variables. This rather subjective method is recommended in the literature (Walter, 1984). The dependent variables obtained for analysis purposes were:

-Perceived time-of-contact with the landing surface, defined by the difference between time of initiation of the EMG activity in the landing related muscles, and the time of touchdown. It is the period left to the falling observer to act, from the moment he perceives that action must be initiated before collision.

-Total flight time, defined as the difference between the time of release indicated by a sudden drop in voltage (from 1.25 volts to 0.1 volts within 1 msec), and time of touchdown.

-First peak of vertical ground reaction forces (PFP), defined as the first sudden increase in pressure exerted over the force plate upon touchdown.

-Time to first peak (TFP), defined as the lapse of time from the moment of touchdown until the point in time in which the first highest-magnitude peak is observed.

-Peak of the second peak (PSP), defined as the highest-magnitude peak of the second increase in vertical forces exerted over the force plate, which was usually the largest in area.

-Time to the second peak (TSP), defined as the time lapse from the moment of touchdown until the moment of second increase in vertical ground reaction forces.

-For the frontalis muscle, activity was defined as a burst of EMG, initiated during the flight or immediately after release. The burst was considered significant when it was maintained during periods longer than 30 msec at an amplitude clearly surpasing the resting levels. Based on this methodology, the percentages of trials in which EMG activity occurred were obtained.

-For the five lower limb muscles, activity before release was defined as EMG bursts taking place within a range of 250 msec before the subject opened the switch. The same criteria were used in this case to determine the percentages of trials that presented activity before the initiation of the fall.

In order to explore if any relationship constrained the different muscle groups to act in a co-ordinated manner, correlation coefficients between the initiation times of 4 muscles were calculated. Similarly, correlation coefficients for the peak forces and time to peak forces were determined as well.

The main hypothesis under investigation required a Goodness-of-Fit method to examine the type of relationship existing between t_c (defined as the period between the time of initiation of EMG activity t_i, until the moment of touchdown) and total flight time (t_d). This analysis was performed for both visually guided and blindfolded trials (the latter did not allow subjects to perceive the time-to-contact variable based on optic information). A 3-way ANOVA with RM on all factors (2 visual 'conditions' x 2 best-fitting 'models' x 2 'muscles') with $\underline{Z_r}$ scores being the dependent variable was carried out to determine any effect due to the factors, in particular the linear versus the exponential saturation 'model'. In the same vein, a regression analysis was done for the first and second order polynomials for both individual cases and pooled data. This procedure was carried out to test the significance of the differences in the residuals accounted by the linear and quadratic models.

Times of onset of EMG activity were obtained from two muscle groups identified as relevant in the preparation for landing, i.e., gastrocnemius and rectus femoris. EMG activity was evaluated following Walters' criterion (1984) based on amplitude and duration of the bursts. The activity of the frontalis was recorded in order to provide an indication of any startle activity taking place during the performance. Frequency histograms for the activation of this muscle as a function of the condition and the height of fall were plotted. Thereafter, the differences were statistically assessed by performing a 2-way ANOVA with RM on both factors, 'condition' and 'heights' (percentage of active trials as the dependent variable). Post-hoc comparisons for the significant interaction showed the significance level reached by specific pair-wise differences.

Similarly, percentages of active trials in which activity of the rectus femoris and gastrocnemius muscles were observed within 250 msec before release. An histogram for the rectus femoris percentages of pre-release active trials was plotted, since this was the only muscle that had a large activity 250 msec before release. A 2-way RM ANOVA was carried out to examine the effects of 'conditions' and 'heights' in the activation before release.

With regard to the analysis of the vertical components exerted on the force platform after touchdown, 6 times two-way RM ANOVA (2 'conditions' x 4 'heights') were done (one per subject, each subject 6 repeated trials per height of fall), with peak of the second peak (PSP) being the dependent variable. This procedure was intended to determine whether averaging across subjects was a reasonable step in following analyses based on vertical ground reaction force variables.

For the first peak of force (PFP) a frequency histogram was obtained in order to visualize the percentage of trials, within different heights of fall, that did indeed have this first peak. Since it was found that only in the two highest categories this peak was present, a 2-way ANOVA (2 'conditions' x 2 'height') with repeated measures on both factors was performed, with peak-first-peak (PFP) being the dependent variable. This analysis was expected to reveal any effects of 'conditions' or 'heights' on the magnitudes of the peak. In the same vein a 2-way ANOVA (2 'conditions' x 2 'height') with repeated measures on the two factors was done with time to first-peak (TFP) as the dependent variable.

For the second force-related measures the analyses followed the same rationale. A 2-way ANOVA (2 'conditions' x

4 'height') with repeated measures on both factors was done, with peak-second-peak (PSP) as the dependent variable. In light of the observed main effect for 'heights', post-hoc (Tukey HSD) comparisons followed to obtain information about specific differences. For the time to second-peak of force (TSP) a 2-way ANOVA (2 'conditions' x 4 'height') with repeated measures on both factors was carried out. Tukey (HSD) post-hoc comparisons were done for the same reason as in the case of the PSP.

The multiple analyses of variance were performed rather than a 2-way RM MANOVA due to the fact that the dependent variables' cells largely outnumbered the number of cases.

All off-line statistical analyses were performed using compatible statistical programs (MacSS and StatView) ran on a Macintosh SE microcomputer. Alpha ($\underline{\alpha}$) was set at $\leq .05$.

6. **Results and Discussion**

6.1. Pilot study.

A pilot study was carried out to provide initial information about the task at hand, and to make final adjustments if necessary.

6.1.1. Left versus right limb homologous muscles.

The preparation for landing involves functionally specific muscle groups. One of the concerns raised was related to the criterion used to differentiate between those muscles relevant for the landing preparation (Greenwood and Hopkins, 1976a, b) and those which were not.

In this case, only one subject was tested in order to determine whether left vs. right limbs were synchronized in the preparation for landing during the flight path. The subject performed trials distributed over two sessions during which a large amount of free-falls (60 per session) took place from heights ranging 5-130 cm (10 trials, 6 height categories). The observations made on recordings of four muscle groups (soleus and tibialis anterior of both legs) confirmed that both limbs work together. The contralateral patterns were similar while their onset of activity occurred at nearly the same time. Further evidence of this symmetry on both sides of the saggittal plane is provided by Smith

(1975) in an investigation on the forces acting upon limb structures while performing an identical landing task (from approx. 1 m height). Hence, it was decided that for the matter under investigation it was not necessary to record EMG activity from homologous muscles.

6.1.2. Muscles exerting torques over one or two articulations.

With regard to which muscle groups should be selected for recording, it was initially thought that muscles which act upon a single joint should be chosen, since their activity was expected to correlate with the changes in the respective joint angle, e.g., the soleus, the vastus lateralis, and the tibialis anterior muscle. Nevertheless, the soleus muscle is only well defined in athletic subjects, and it is difficult to localize in other individuals. Its activity may be often mixed with that of the gastrocnemius. In this case, the results obtained from two subjects in a total of 120 trials (2 conditions x 6 heights x 10 trials), suggested that in spite of the differences in location, these two muscles present virtually identical patterns. Therefore, during the experiment it was decided to collect data only from the medial gastrocnemius, since the soleus activity was regarded as redundant and inconvenient for recording, especially with surface electrodes.

6.1.3. Functional discrimination between preparatory and post-landing muscles.

From the pilot study it was not possible to determine any clear criterion to discriminate, in a broad sense, between relevant and irrelevant preparatory muscles for the landing task. This became possible only after the preliminary data analysis, in which functional distinctions could be made. Primarily, there were muscle groups consistently active during the flight path, and thus, assumed to be relevant for the preparation to land. Their onset of activity presented relatively low variability and consistent patterns across the different height categories. It was possible to identify muscles that were consistently active only after touchdown, while during the flight path their activity presented large variability, and they were active in a smaller percentage of the trials depending on the height, the condition, and the performer. The frontalis muscle was 'a priori' considered functionally irrelevant, and its action was expected to indicate the presence of startle reflexes in no-vision conditions.

6.1.4. Selection of 'height of fall' categories.

In this part of the preliminary study one subject performed landings from six different heights (5 cm, 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm) in both conditions (60 trials for vision, and 60 trials in no-vision condition). However, fatigue was observed, thus the number of heights was reduced to four. In addition, the subject reported difficulties when landing blindfolded from the highest height, hence the falling heights were rearranged in four categories (lowest = 5 cm, low = 20 cm, high = 60 cm, and highest = 90 cm). The theoretically calculated flight times for falling bodies from these heights at constant gravitational acceleration are: 101 msec, 202 msec, 350 msec, and 429 msec, respectively. Nevertheless, the empirical flight durations were often somewhat reduced when the subject performed the landings, in spite of the fact that the heights were strictly measured several times during the session. A delay in the data collection process or a delay caused by the switch mechanism, were hypothesized. A test was designed to examine the differences. A heavy object was dropped from 3 different heights (low = 20 cm, medium = 50 cm, and high = 100 m). These results were then compared to the theoretical values. It was found that there was no delay existing in this case. In fact, the empirically measured flight times obtained from dropping the object were within a range of ±2 msec of the theoretical flight duration for the respective heights. Thus, it was concluded that these differences (between human subjects and inanimate objects) should be experimentally

controlled by pre-setting appropriate height of fall ranges that permitted to obtain the flight times durations needed during the testing session. The reason for these differences seems to be unconscious, caused by a reaction of the subjects upon release. There appeared to be a tendency to keep the contact with the overhead bar as long as possible by sliding down until the effort of the hand to remain suspended was overcome by the weight of the body. In addition, it seemed that subjects relaxed their muscles voluntarily just before release, but not while measurement of the height of fall took place (especially the shoulder girdle depressors). These two factors reduced the flight times in most of trials during the actual tests later in the experiment. This phenomenon may only be understood in light of the psychological benefits that 'shortening' the flight duration could bring (in terms of impacts on body structures, probably there would not be a great reduction of injury risks). Based on this finding, four height of fall ranges (5-10 cm, 20-25 cm, 60-65 cm, and 90-95 cm) were stipulated during the actual tests to compensate for the tendency to decrease flight durations. Moreover, the heights were measured from the big toes at a plantar flexion position, after the subject relaxed the feet while suspended from the overhead bar and after being instructed to extend the upper body.

6.2. Results from the EMG data analysis.

6.2.1. Muscular activity relevant in the preparation to land.

The main hypothesis of this work relates to the timing strategies adopted by subjects during landing performances in order to prevent injuries at collision with the substrate. Of particular interest was the role of the visual system.

According to the Direct Perception approach (Gibson, 1979) the information available in the environment is immediately perceived as the individual moves through it. This causes a constant flow of information at the optic array, an 'optic flow field'. The 'T strategy' proposed by Lee (1974, 1976, 1980a, b) has been forwarded as a plausible heuristic. This investigation was aimed at assessing the extent to which this strategy may be used by human subjects in timing their response in preparation for landing. The time of initiation of muscular activity was expected to indicate when, during the flight path, individuals perceived that the optic variable $\tau_{(t)}$ has reached a critical value $\tau_{(m)}$.

The initial findings indicated that not all muscle groups seem to be consistently active during the flight. The tibialis anterior muscle was generally inhibited, while its agonist during plantar flexion (the gastrocnemius) was undoubtedly active in most of the cases. Fukuda et al. (1987)

reported as well that the tibialis anterior muscle is not active before touchdown in 2 out of 5 of the performers, in landings on a stiff platform. This muscle, however, was largely active during the post-landing period (Fukuda et al., 1987). Hence, the tibialis anterior was eliminated for analysis purposes. With regard to the biceps femoris, its activity was not easily recorded, and it was largely variable depending on the subject and the landing condition. The activity of the vastus lateralis was not always present as in the cases of the gastrocnemius and the rectus femoris muscles. When this muscle did show activity during the flight, its initiation was also largely variable. Non-defined patterns were observed in the curve-fitting process due to the scatter of these data points.

In light of the activity seen in particular muscles during the pre-landing period, as opposed to others mainly active during the post-landing one, the idea of existing functional synergies (Lee, W., 1984) was regarded as feasible. Correlation coefficients were calculated for the different muscle groups in the task. The results are shown in the correlation matrices below (Tables 1a and 1b).

Table 1a <u>Correlation matrix muscular activity initiation recorded from 4 muscles groups in **vision** condition in six subjects</u>.

	SUBJECTS					
Pairs	1	2	3	4	5	6
GA-RF	.60**	.81**	.84**	.81**	.50*	.82*
GA-BF	.38	.77**	.73**	.69**	.64**	.75**
GA-VL	.25	.58*	.88**	.78**	.48*	.56*
BF-RF	.44	.74**	.69*	.68**	.46	.92**
BF-VL	-.20	.68**	.60*	.64**	.20	.72**
RF-VL	.21	.72**	.83**	.82**	.75**	.64*

* $p \leq .05$

** $p \leq .01$

Table 1b Correlation matrix muscular activity initiation recorded from 4 muscles groups in **no-vision** condition in six subjects.[4]

	SUBJECTS					
Pairs	1	2	3	4	5	6
GA-RF	.74**	.52*	.82**	.60**	.76**	.64**
GA-BF	.86**	.42	.57*	.57**	.62*	.54*
GA-VL	.64*	.51	.92*	.59**	.49*	.66**
BF-RF	.63**	.78**	.46	.71**	.46	.56*
BF-VL	.49	.81*	.90*	.58**	.23	.30
RF-VL	.59	.85**	.84*	.49*	.81**	.69**

* $p \leq .05$

** $p \leq .01$

At significance levels of $p \leq .05$ and $p \leq .01$, the coefficients indicate that the different muscles seem to be affected by common underlying constraints giving place to a coordinative structure (Easton, 1978). This is the case in 81% of the pairs in the vision condition, and in 78% of the

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[4] GA: gastrocnemius, RF: rectus femoris, BF: biceps femoris, VL: vastus lateralis. The same abbreviations are valid for table 1 a.

pairs in no-vision conditions. These scores, however, should be interpreted with caution. For instance, the number of degrees of freedom of the gastrocnemius and the rectus femoris were lowered when correlated with the biceps femoris and the vastus lateralis, since the latter were not active in a large percentage of the trials. The gastrocnemius-rectus femoris pair, nonetheless, showed coefficients that may be representative of a coordinated action, suggesting that changes in the time of initiation of one of these muscles is accompanied by subsequent changes in the other, and therefore, providing some support for the hypothesized functional synergy in the pre-landing stages.

With regard to the activity of the frontalis muscle, this was measured to indicate the presence of startle reflexes occurring after release as observed during unexpected falls in other reported experiments (Greenwood and Hopkins, 1976a). This reflexive activity often appeared in the landing related muscles (Melvill Jones and Watt, 1971a, b), and in the upper limb muscles as well (Greenwood and Hopkins, 1976a, b) at a latency of onset of 75-90 msec after release, and it ended after 200 msec (Greenwood and Hopkins, 1980). However, since subjects in this experiment performed landings in self-release voluntary conditions, it was hypothesized that reflexive activity will not be present, at least in vision conditions. Greenwood and Hopkins (1976a) found that the initial burst of activity, interpreted as a 'startle reflex' to sudden falls, was inhibited in all muscles <u>including the periocular ones</u>, when subjects released themselves. In this study the frontalis muscle was largely active at the time the voluntary EMG activity was also observed in the landing related muscles (i.e., the second burst), in spite of the fact that subjects release themselves at their own will. It seemed that its activity was not related to startle reflexes observed in the limbs, in contradiction with the observations reported by Greenwood and Hopkins (1976a)

The following histograms show the percentage of active trials of the frontalis muscle for the performance of each subject from 4 'heights' of fall and 2 'conditions'.

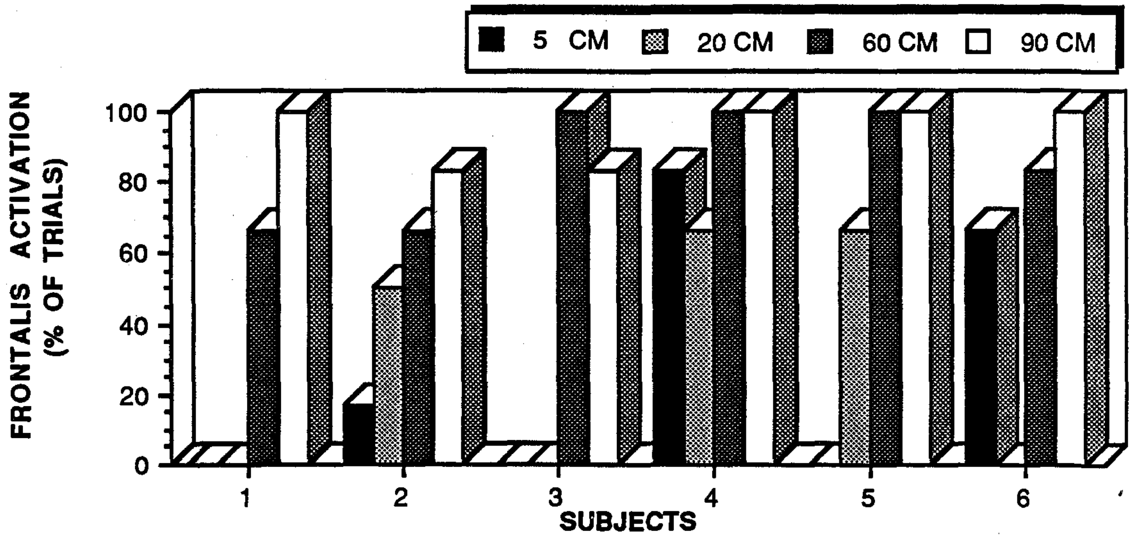

Figure 4a Frontalis muscle activation in 4 heights of fall (**vision** conditions across 6 subjects).

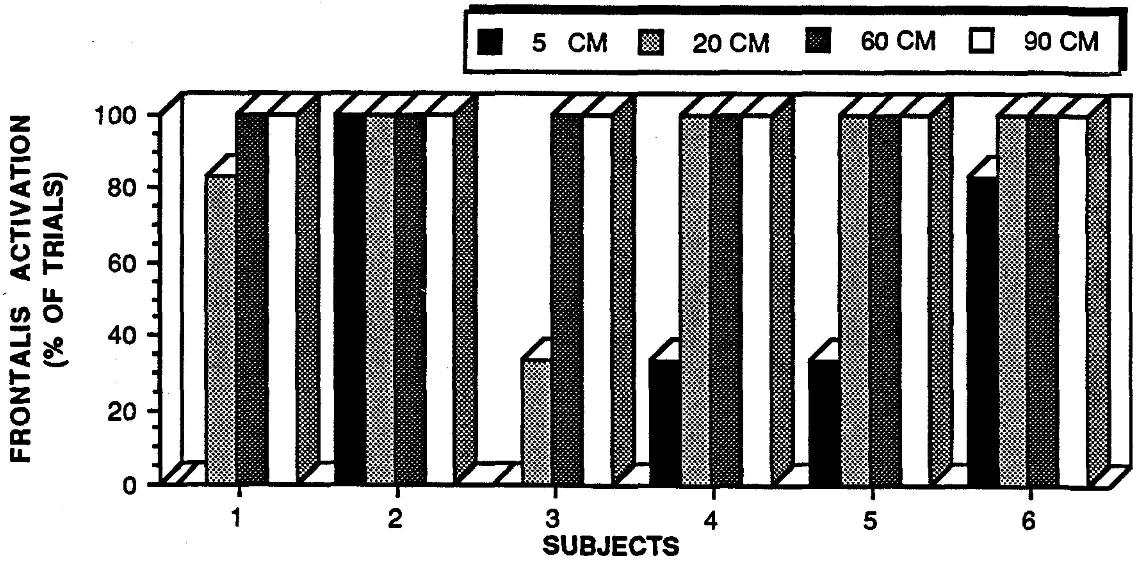

Figure 4b Frontalis muscle activation in 4 heights of fall (**no-vision** conditions across 6 subjects).

The main effects were assessed by carrying out a 2-way RM ANOVA (2 'conditions' x 4 'heights') on both factors. The results showed that the main effect for 'conditions', the main effects for 'heights', and the interaction between these factors all were significant ($\alpha \leq .05$). Table 2 shows the results.

Table 2 Results of the analysis of variance on the percentage of activation of the frontalis muscle across 6 subjects.

MAIN EFFECTS	**d.f.**	***F* value**	**prob. F**
Heights	3, 15	9.55	.027
Conditions	1, 5	13.47	.001
Interaction	3, 15	54.85	.015

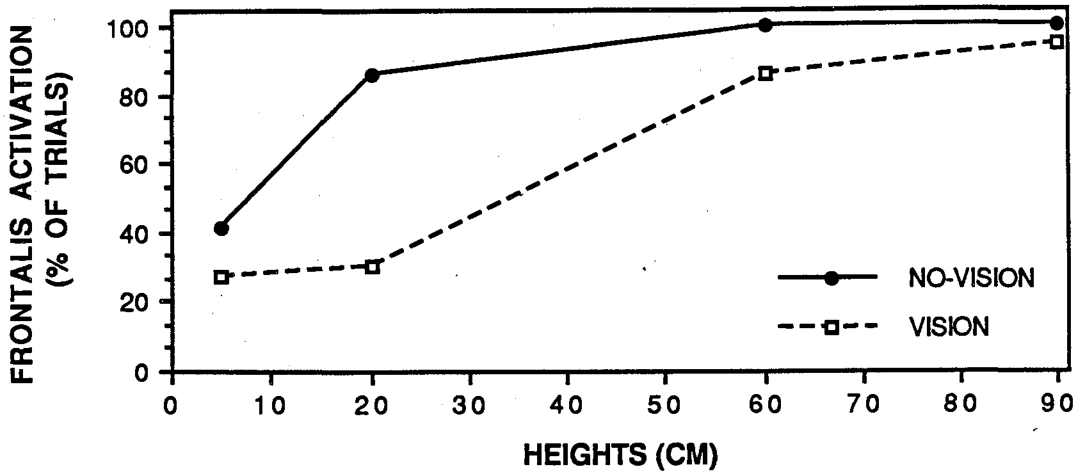

Figure 5 Main effects and interaction for the frontalis muscle activation in 2 'conditions' and 4 'heights' of fall.

The results shown can be interpreted as evidence for the existence of startle activity representative of different arousal states in conditions in which visual cues are eliminated. However, the presence of EMG signals obtained from the frontalis muscle (presumably unrelated to landing), was observed regardless of the onset of the first EMG burst, which is inconsistent with the results reported by Greenwood and Hopkins (1976a) in unexpected falls. These EMG bursts in the frontalis muscle were observed in spite of the 'self-release falls'. The percentage of activation was significantly larger in the absence of visual cues, supporting the hypothesis that startle responses may be evidenced in the no-vision conditions. Nonetheless, when visual guidance was available activity was also observed, although not at such high percentages as when the subjects were unable to see. In addition, the effects of heights on the activation of this muscle reveals that for the highest landings subjects showed startle activity more consistently. More interesting, however, is the significant interaction found. It can be observed that beyond the 20 cm height category there is a sharp increase in percentage of trials showing this startle response to initiation of the fall, particularly when subjects were blindfolded. In the lowest height, however, the visual condition did not seem to affect the subjects response. Post-hoc comparisons were done for the significant interaction to get further insights on these effects in specific pair-wise cases. The results are shown in the table 3a and 3b.

Table 3a Differences between percentage of activation of the frontalis muscle for **vision** condition and 4 heights of fall (marginal means and significance of the differences).

	HEIGHTS (CM)			
	5	**20**	**60**	**90**
Marg.Means	27.78	30.55	86.11	94.44
5	-	2.77	58.33**	66.66**
20		-	55.56**	63.89**
60			-	8.33
90				-

* $\alpha \leq .05$

** $\alpha \leq .01$

Table 3b Differences between percentage of activation of the frontalis muscle for **no-vision** condition and 4 heights of fall (marginal means and significance of the differences).

	HEIGHTS (CM)			
	5	**20**	**60**	**90**
Marg.Means	41.66	86.11	100	100
5	-	44.45*	58.34**	58.34**
20		-	13.89	13.89
60			-	8.33
90				-

* $\alpha \leq .05$

**$\alpha \leq .01$

In light of the finding that activity of muscles unrelated to landing occurs independently of the appearance of the first burst of activity in response to the fall (Melvill Jones and Watt, 1971a, b), it appears that preparation for landing is neither strictly a voluntary or a reflexive mechanism.

6.2.2. Analysis of the landing strategy in vision conditions:

The time period between the moment of initiation of EMG activity (in the gastrocnemius and the rectus femoris muscles) and the moment of touchdown defined the limits of the perceived time-to-contact with the ground. This preparatory period was analyzed in order to unveil the timing strategies used by the performers. For the vision condition the τ heuristic was hypothesized, in that it allows an immediate temporal estimate of the moment when action should be initiated, i.e., when the optic variable τ reaches a critical value $\tau_{(m)}$ based on the time-to-contact (t_c).

Accordingly, $t_c = t_d + \tau_{(m)} - (\tau_{(m)}{}^2 + t_d{}^2)^{1/2} - t_a$,

where t_a is a time-delay between perception of $\tau_{(m)}$ and the moment of initiation of EMG activity.

The hypothesized best-fit for such model would follow an exponential saturation curve for which $y = A \cdot (1 - e^{n \cdot x})$ (Spain, 1982), approaching an asymptote 'A' as flight time increased, while 'n' is always negative. An estimation of the value A was required by the program in order to proceed with appropriate calculations of the regression line. This estimation was assumed to be never shorter than a visual pre-motor reaction time ($\geq$ 120 msec).

For the no-vision condition a 'linear model' was hypothesized, since subjects were expected to start acting at a constant time after release, i.e., their action was not expected to be related to the moment of landing, but to the moment of initiation of the fall. Therefore, as the flight time increased, linear increments in time-to-contact were expected.

The Goodness-of-Fit technique by the linear least squares procedure (Spain, 1982) was used to compare the obtained results to the theoretical curves. Extremely high or low scores were eliminated after evaluating their effects on the predicted Y' values, and after inspecting carefully the obtained plotted results. This procedure was motivated by the certain characteristics of the linear least squares process which involves a transformation of the data to linear form (l_n). As a result, there is a tendency to cluster extreme values, and negative or zero values are not suitable for this transformation. The weight of very high or low scores becomes increased, and therefore it distorts the best-fit. In addition, the algorithm used for the exponential saturation model relies on the assumption that a zero value of X corresponds to a zero value of Y, and therefore the curve must start at zero. To overcome this assumption, the scores of each single curve were shifted by subtracting a constant equal to the lowest score of the given X and Y set of values.

The empirical and the theoretical results were then plotted on a graphics application (Cricket Graph) ran on a Macintosh SE microcomputer.

For one of the subjects (figure 7c) the number of degrees of freedom was notably reduced in the vision condition, since the rectus femoris was only active during half of the total number of trials. This individual adopted patterns of landing that did not required the use of muscular preparatory activity during the falls from the 5-25 cm categories. In general, the lowest heights of fall did not enhanced preparatory activity in other cases either, and therefore there are fewer data points represented in the best-fitting curves.

When the linear model was applied to the individual's data, the $\underline{r}^2$ values were, for the most part, significantly higher than those resulting from the exponential saturation regression. The results are shown in Tables 4a and 4b.

Table 4a r^2 coefficients for the best-fitting exponential saturation and straight line models for the **gastrocnemius** muscle in vision and no-vision conditions.

	VISION			NO-VISION		
	d.f.	**EXP.**	**LIN.**	**d.f.**	**EXP.**	**LIN.**
S1	18	.265	.706	22	.563	.807
S2	16	.662	.935	15	.655	.795
S3	18	.561	.772	15	.554	.861
S4	18	.635	.823	17	.737	.822
S5	18	.453	.721	20	.725	.837
S6	15	.824	.866	17	.893	.890

Table 4b r^2 coefficients for the best-fitting exponential saturation and straight line models for the **rectus femoris** muscle in vision and no-vision conditions.

	VISION			NO-VISION		
	d.f.	**EXP.**	**LIN.**	**d.f.**	**EXP.**	**LIN.**
S1	16	.686	.701	15	.428	.586
S2	14	.657	.722	22	.503	.593
S3	9	.342	.521	14	.416	.603
S4	16	.630	.650	22	.498	.538
S5	14	.531	.828	18	.738	.782
S6	17	.572	.634	19	.567	.757

To assess further differences between the two hypothesized models, the *r* coefficients were transformed to Z_r scores, and these were subsequently used as the dependent variable in a 3-way RM ANOVA (2 'conditions' x 2 'models' x 2 'muscles') carried out to determine the effects of these factors on the *r* coefficients, particularly, differences between the linear and exponential saturation models.

The results showed that the only significant effect was observed for the best-fit 'models' factor, this being the *r* coefficients of the straight line relationship was significantly higher than the exponential saturation one. The results are presented in the following table.

Table 5 Results of the 3-way RM ANOVA (2 'conditions' x 2 'models' x 2 'muscles') on *r* coefficients converted to Z_r scores.

MAIN EFFECTS	**d.f.**	**F value**	**pr.of F**
Conditions	1, 5	0.107	0.075
Model	1, 5	8.784	0.031*
Muscle	1, 5	5.006	0.074
Cond.x Mod..	1, 5	0.119	0.739
Cond.x Musc.	1, 5	1.472	0.279
Musc.x Mod.	1, 5	1.465	0.280
Cond.x Mus.x Mod.	1, 5	0.471	0.527

* $\alpha \leq .05$.

These results gave an initial indication of the strategy used by subjects. In continuation with the procedures to assess the most representative model, a regression analysis using first and second order polynomials (linear and quadratic) was carried out in order to verify the significance of the straight line relation already observed. The test of significance of differences between the residuals (_t_-test) of the first and the second order polynomials shows that, in general, the linear fit seemed to be favored. That is, there were only a few cases in which additional sources of variability were accounted for by the addition of a quadratic term. The probability for the differences between _r_ coefficients (i.e., a ratio between the sum of squares of the regression SS_{reg} over the sum of squares of the residuals SS_{res}) is presented in the Table 6a and 6b.

Table 6a *r coefficients, differences between r linear and r quadratic (Δ_r), and probability associated with the difference, for the gastrocnemius muscle for each subject in both visual conditions*.

	VISION			**NO-VISION**		
	LIN.	**QUADR.**	Δ_r	**LIN.**	**QUADR.**	Δ_r
S1	.840	.913	.073*	.899	.917	.018
S2	.967	.975	.008*	.892	.892	.000
S3	.880	.917	.037*	.908	.912	.004
S4	.907	.914	.007	.907	.925	.018
S5	.849	.852	.003	.915	.918	.003
S6	.930	.932	.002	.944	.944	.000

* $p \leq .05$

Table 6b *r coefficients, differences between r linear and r quadratic (Δ_r), and probability associated with the difference, for the rectus femoris muscle for each subject in both visual conditions*.

	VISION			**NO-VISION**		
	LIN.	**QUADR.**	Δ_r	**LIN.**	**QUADR.**	Δ_r
S1	.837	.837	.000	.766	.770	.006
S2	.850	.887	.037	.770	.828	.058*
S3	.722	.784	.062	.776	.793	.017
S4	.806	.824	.018	.733	.744	.011
S5	.910	.925	.015	.884	.910	.026*
S6	.796	.824	.028	.870	.871	.001

* $p \leq .05$

The pooled data points showed a somewhat clearer picture. The first order polynomial accounted for most of the differences between residuals in the case of the gastrocnemius muscle in both visual conditions. In the case of the the rectus femoris muscle in no-vision conditions, the results showed that addition of a quadratic term to the linear model, accounted for the variability in a significant manner, while in the vision conditions the results still remained unconfirmed whether the linear fit was the best (this was probably due to the large variability of the data points). However, the plotted results seem to follow an exponential curve positively accelerated, and therefore this is opposite to the increases in the perceived time-to-contact predicted by the $\tau_{(m)}$ model . The results are shown in the next table and they are illustrated in the following figures.

Table 7 r coefficients, differences between r linear and r quadratic (Δ_r), and probability associated with the difference, for pooled data obtained from the gastrocnemius and the rectus femoris muscles in both visual conditions.

	VISION		**NO-VISION**	
	GA	**RF**	**GA**	**RF**
Linear (x)	.797	.639	.735	.739
Quadr. (x^2)	.800	.648	.741	.768
Diff. (Δ_r)	.003	.008	.006	.029*

*$p \leq .05$

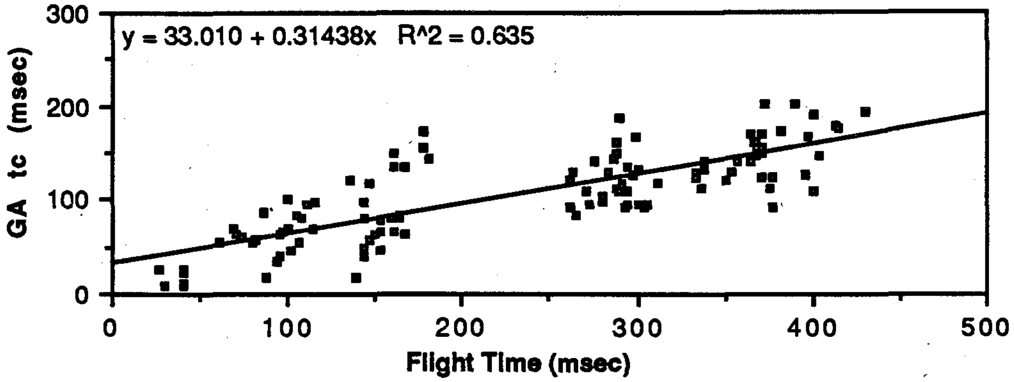

Figure 6a Best-fitting curve for the gastrocnemius muscle in vision conditions.

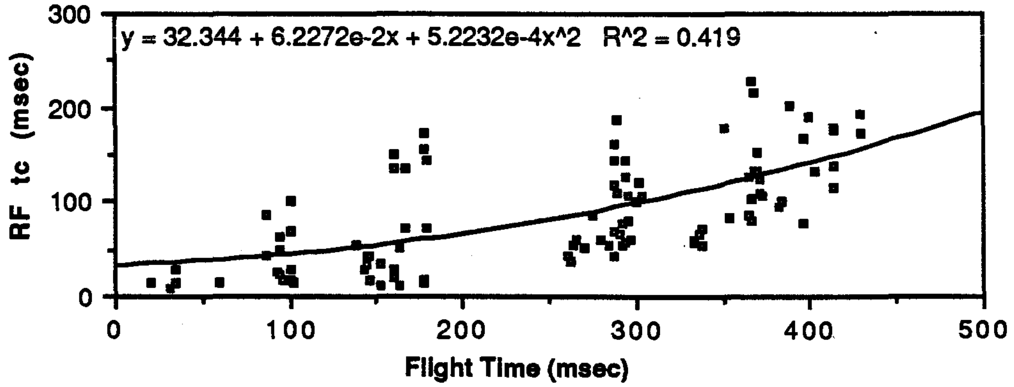

Figure 6b Best-fitting curve for the rectus femoris muscle in vision conditions.

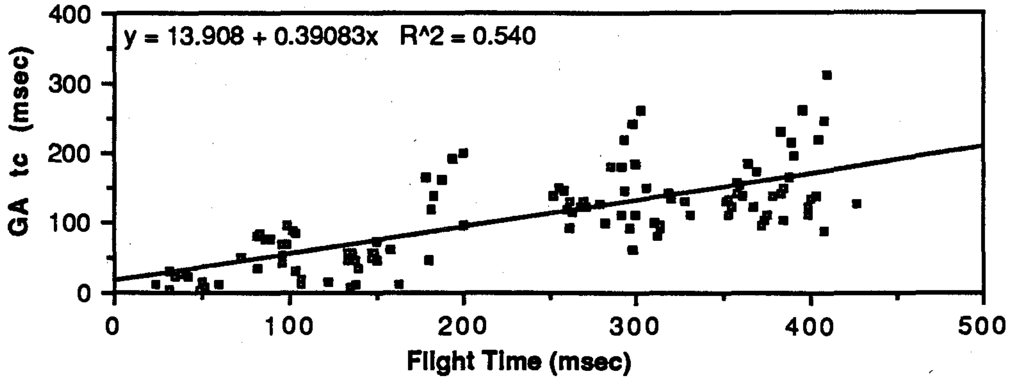

Figure 6c Best-fitting curve for the gastrocnemius muscle in no-vision conditions.

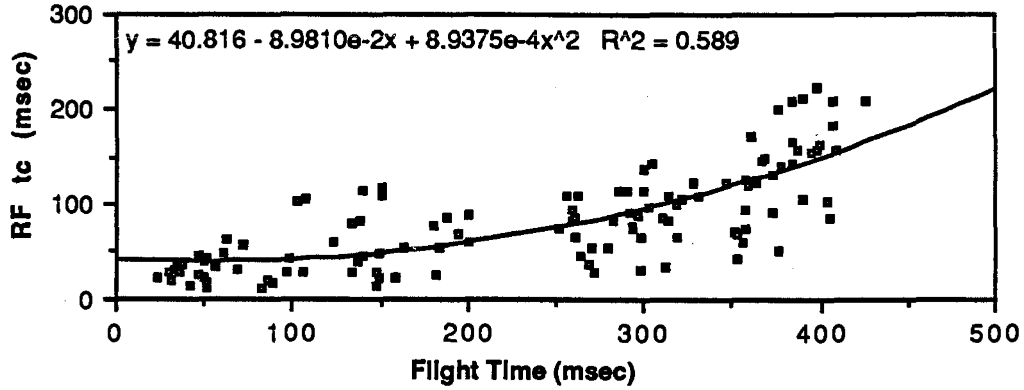

Figure 6d Best-fitting curve for the rectus femoris muscle in no-vision conditions.

In light of the above, the strategy used by falling subjects in the preparation for landing seems to be best represented by the straight line relationship, i.e., subjects started their actions at a constant time from the moment of release, thus the time-to-contact variable increased linearly with increases in flight time.

6.2.3. The strategy in no-vision conditions.

In the blindfolded conditions the same analysis was performed. The results showed that when vision was occluded, subjects seemed to follow a linear strategy based on the moment of release in order to initiate their action. This trend was observed in both muscles recorded when the results were compared to the exponential saturation model. The linear model was confirmed by the regression analysis in the gastrocnemius muscle, while in the case of the rectus femoris the scatter of the data points appeared to influence the results, and thus, in the vision conditions the results obtained from this muscle (Table 7) showed that neither the first nor the second order polynomial could account for the variance around the regression line. The results from the no-vision conditions in the rectus femoris showed that the quadratic model was the most representative. It is clear from our results, at least as an argument by default, that the negatively accelerated relationship expected if subjects were using the T strategy, did not find any support. Therefore, this optically based model did not seem to be applied under the present experimental conditions in the landing task.

In general, there was no apparent difference in the timing strategy used for the preparatory landing response whether visual cues were available or absent (see results of Table 5). The following graphs (figure 7a-7f) show the best-fitting straight lines for vision and no-vision conditions for each subject's muscular activity in the gastrocnemius and rectus femoris muscles.

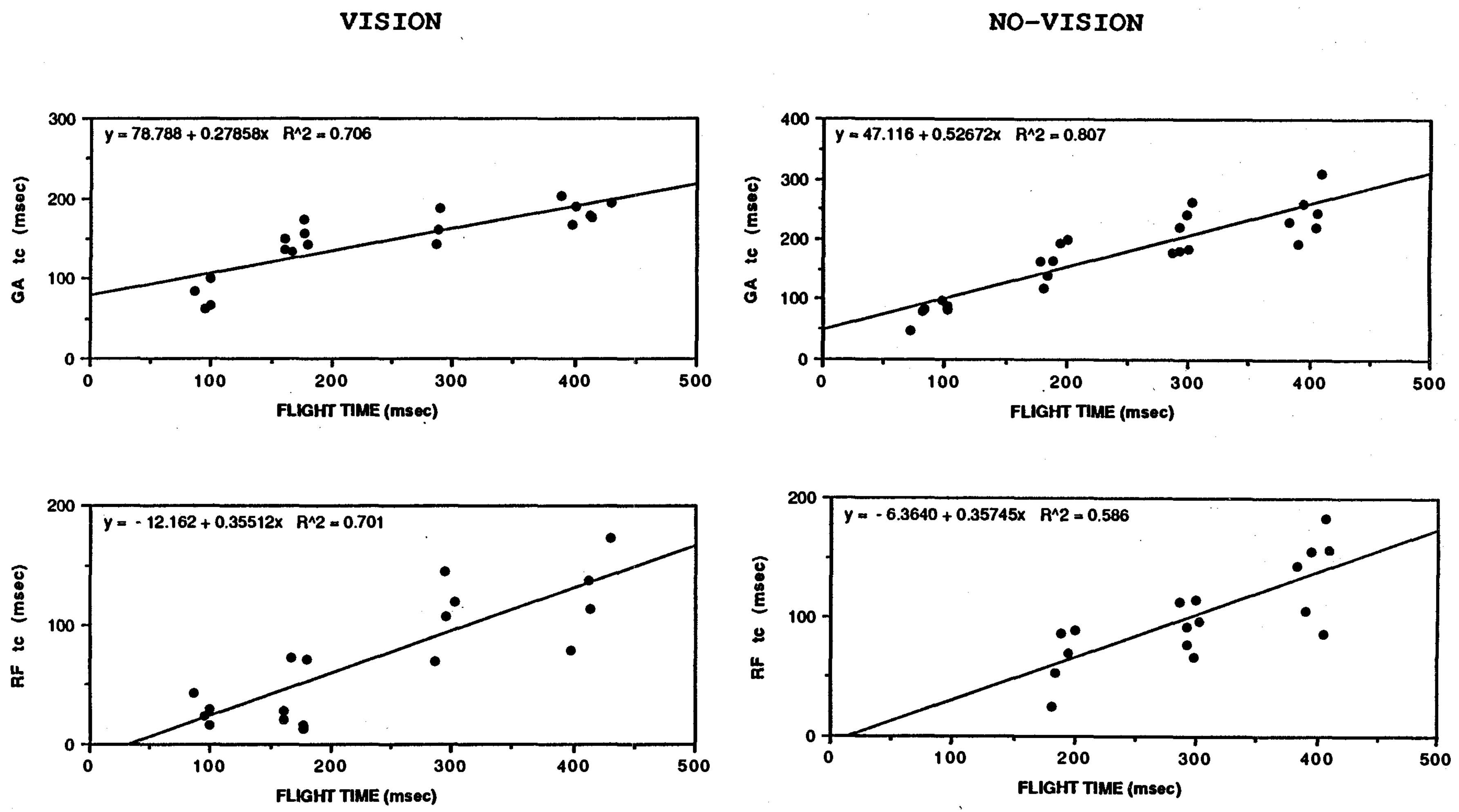

Figure 7a:Best-fitting straight line between perceived time-to-contact and flight time for subject 1 (values obtained from EMG onsets in the Gastrocnemius and Rectus Femoris muscles, in vision and no-vision conditions).

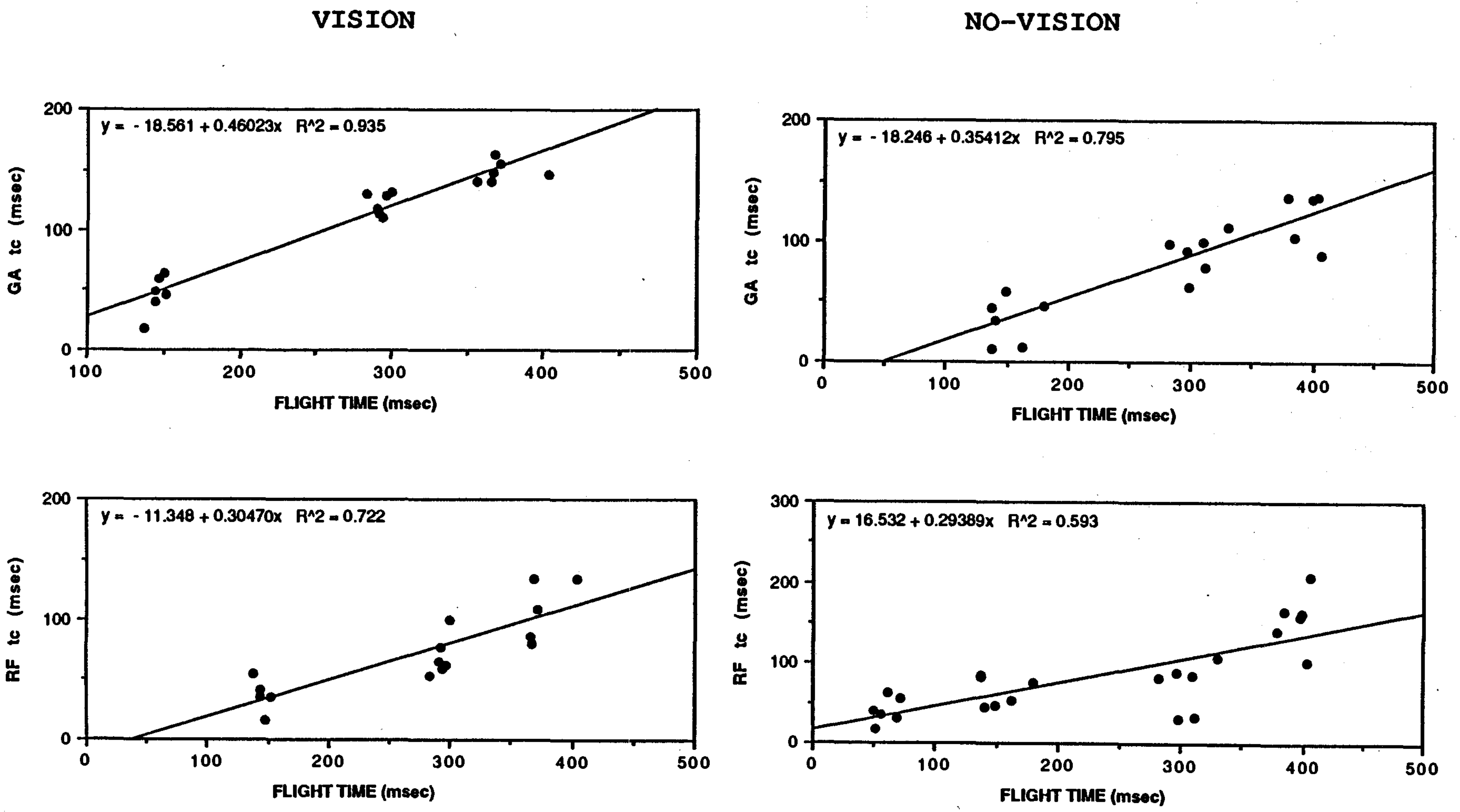

Figure 7b:Best-fitting straight line between perceived time-to-contact and flight time for subject 2 (values obtained from EMG onsets in the Gastrocnemius and Rectus Femoris muscles, in vision and no-vision conditions).

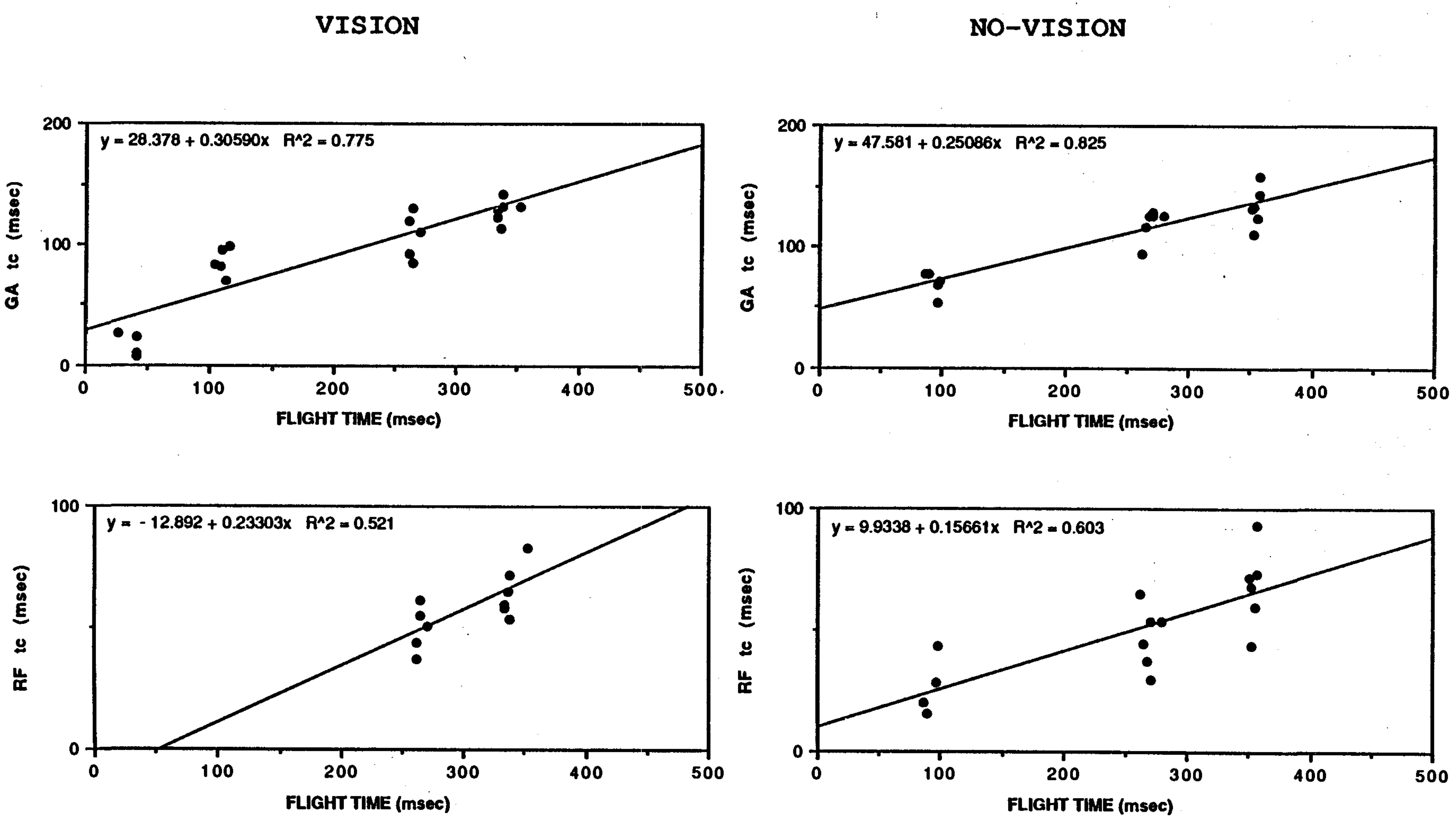

Figure 7c:Best-fitting straight line between perceived time-to-contact and flight time for subject 3 (values obtained from EMG onsets in the Gastrocnemius and Rectus Femoris muscles, in vision and no-vision conditions).

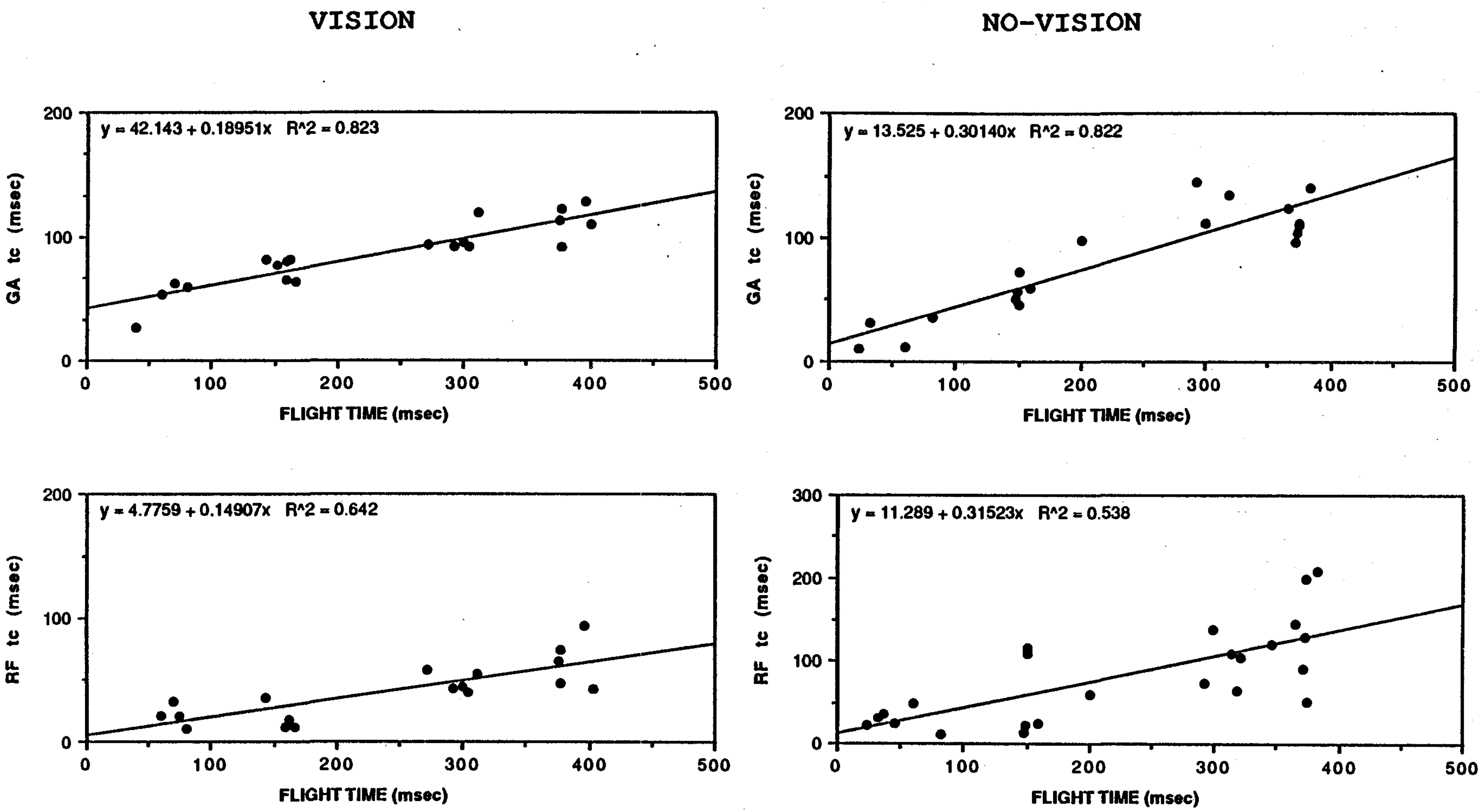

Figure 7d:Best-fitting straight line between perceived time-to-contact and flight time for subject 4 (values obtained from EMG onsets in the Gastrocnemius and Rectus Femoris muscles, in vision and no-vision conditions).

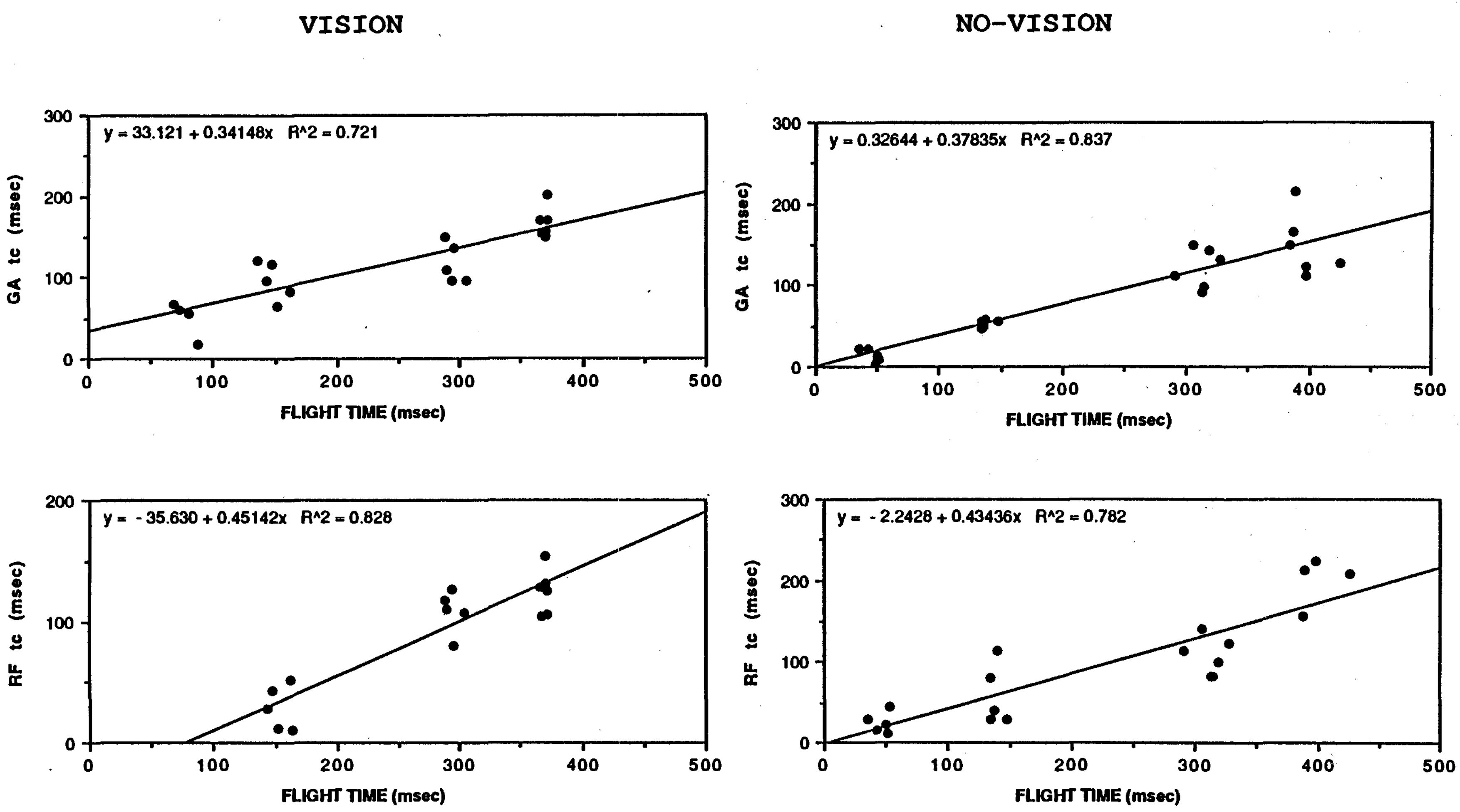

Figure 7e:Best-fitting straight line between perceived time-to-contact and flight time for subject 5 (values obtained from EMG onsets in the Gastrocnemius and Rectus Femoris muscles, in vision and no-vision conditions).

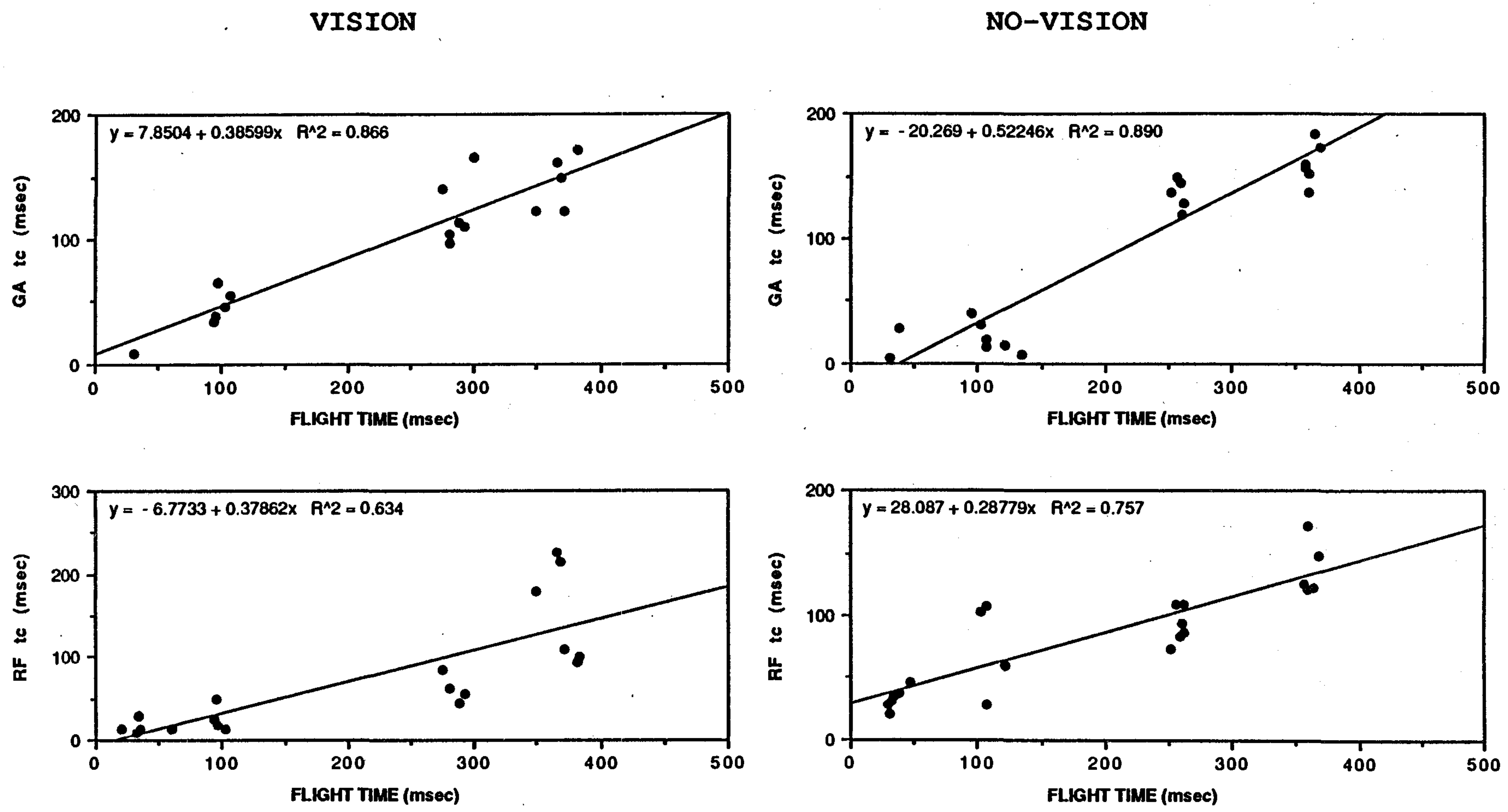

Figure 7f:Best-fitting straight line between perceived time-to-contact and flight time for subject 6 (values obtained from EMG onsets in the Gastrocnemius and Rectus Femoris muscles, in vision and no-vision conditions).

6.2.4. Muscular activation 250 msec before release.

Melvill Jones and Watt (1971a, b) reported findings that landings from heights lower than 5 cm (≤ 101 msec) do not allow time for the build up of reflexive muscle activity, thus causing a jolt at touchdown. In this experiment it was predicted that self-released subjects would prepare for landing from very low heights before the actual release from the overhead bar in order to compensate for the effects observed by Melvill Jones and Watt. The percentages of active trials (250 msec before release) were calculated for the two relevant muscles. The results are shown in the following tables.

TABLE 8a Percentage of activation of the gastrocnemius muscle (250 msec before release).

	VISION				**NO-VISION**			
	Height (cm)				Height (cm)			
SUBJ.	**5**	**20**	**60**	**90**	**5**	**20**	**60**	**90**
1	50	33	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	17	0	0	0	50	33	0	0
4	33	33	0	0	33	0	0	0
5	50	17	0	0	50	0	0	0
6	17	0	0	17	0	67	67	17

TABLE 8b Percentage of activation of the rectus femoris muscle (250 msec before release).

	VISION				**NO-VISION**			
	Height (cm)				Height (cm)			
SUBJ.	**5**	**20**	**60**	**90**	**5**	**20**	**60**	**90**
1	0	17	50	0	0	33	0	0
2	0	50	0	0	100	100	17	0
3	0	0	17	0	17	83	50	67
4	0	0	83	33	50	17	67	33
5	0	33	0	33	33	33	50	83
6	33	0	0	0	83	67	100	67

One can observe that the preparation before release is muscle-specific. Only 34% of the cells show activity for the gastrocnemius, while for the rectus femoris this percentage is significantly higher (62.5%). It seems plausible to interpret this phenomena in light of the task at hand. The landings were performed after the subjects remained suspended by gripping the overhead bar with their hands. In this rather unusual type of landing task, the center of mass will move up and backwards on the saggittal plane, beyond the base of the body causing a rotational moment at touchdown. As a consequence subjects would fall backwards if they did not bring their center of mass forward, by slightly flexing the hips before release.

With regard to the effects on the activation before release, a 2-way ANOVA (2 'conditions' x 4 'heights') with repeated measures on both factors (% of activation as the dependent variable) showed that for the rectus femoris muscle (the only one to be highly active before release) there was a non significant main effect for 'heights'. It was hypothesized initially that the short flight times in low height landings may not allow time for the build up of muscle tension in unexpected falls, as reported by Melvill Jones and Watt (1971b), and therefore, subjects in self-release conditions were expected to attempt to compensate for this time constraint by preparing for the landing even before release. Nevertheless, this hypothesis did not find support from these data. On the other hand, the rectus femoris activation before release seems to be associated with the 'condition' factor. A significant main effect was found for this factor, suggesting that when visual cues were occluded, subjects prepared for the landing before release, thus providing supportive evidence that subjects were over confident when they relied on their visual information (i.e., when subjects had visual cues available they did not prepare for the landing). The interaction between 'conditions' and 'heights' was not significant. Table 9 and Figure 8 show these results:

Table 9 Results of the analysis of variance on the percentage of activation of the rectus femoris muscle 250 msec before release.

MAIN EFFECTS	d.f.	F value	pr.of F
Heights	3, 15	.350	.792
Conditions	1, 5	8.479	.033
Interaction	3, 15	.454	.721

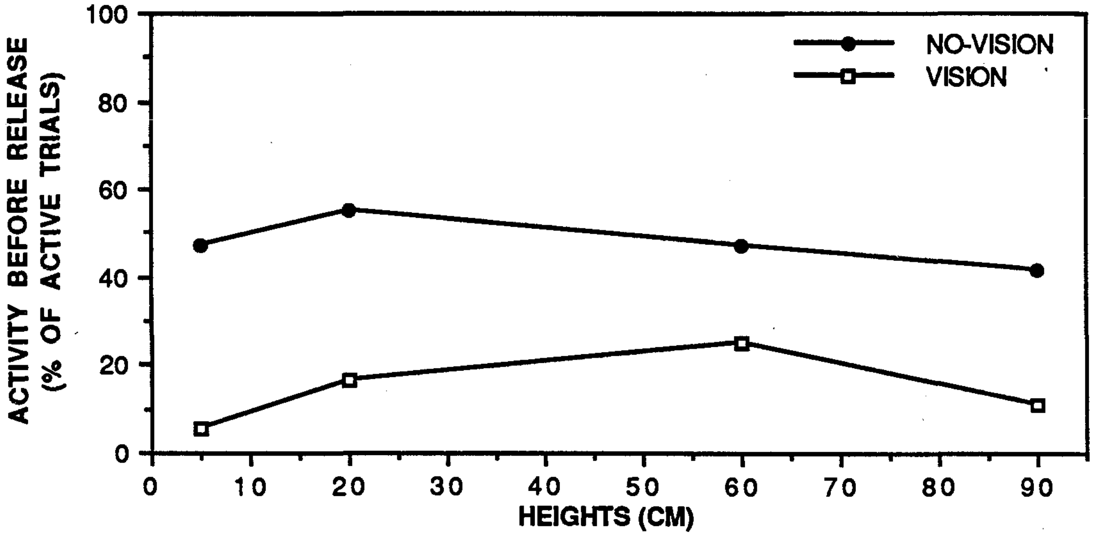

Figure 8 Main effects for 'conditions' in the preparation before release (percentages of active trials for the rectus femoris muscle).

The percentage of activation in both conditions may be, however, largely dependent upon individual factors. In fact this appears to be the case in the activation of the rectus femoris. The histograms below show that for example that subject #6 prepared before release in a large percentage of the no-vision trials regardless of the landing height. Subject #1, in contrast, showed almost no preparatory activity before release in either condition.

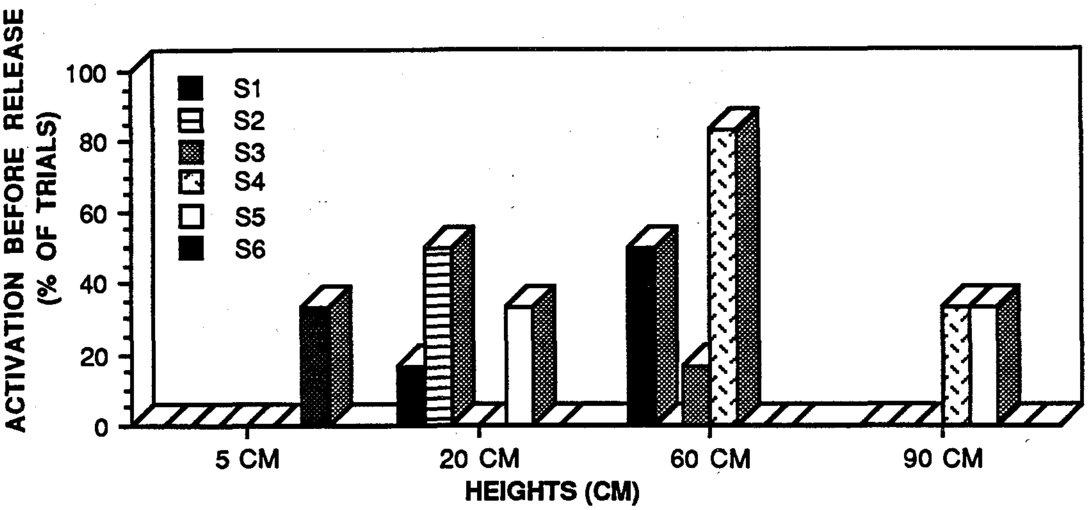

Figure 9a Percentage of activation of the rectus femoris muscle before release, in six subjects in **vision** condition.

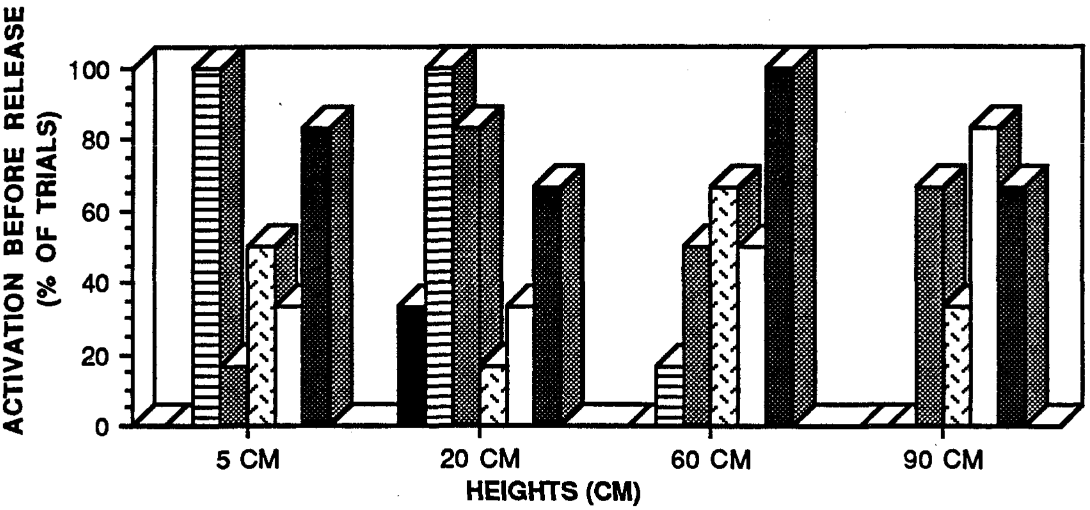

Figure 9b Percentage of activation of the rectus femoris muscle before release, in six subjects in **no-vision** condition.[5]

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[5] The legend of figure 9a is also valid for figure 9b.

To summarize, these results provided evidence that conditions in which there is ongoing visual information and conditions in which visual cues are eliminated do not seem to affect the strategy used by subjects in the landing preparation, at least from heights covering a wide range of those usually observed in real life situations. The T strategy is not applicable in these cases. However, it may certainly be used in situations in which the $T_{(m)}$ reaches values > 250 msec as suggested by Lee et al. (1983), or in unexpected situations. In both visual conditions subjects seemed to adopt a linear strategy.

An analysis on the force magnitudes was done in order to test the effects of this strategy for the vision and no-vision conditions in diminishing the impact at landing. The results are reported in the next section.

6.3. Analysis of vertical ground reaction forces.

6.3.1. Relationship between variables originated from the vertical components of the force plate output.

The similarities between the two conditions were assessed by measuring the landing outcomes. Initially, different strategies were hypothesized to produce differences in the ability to dissipate the momentum gained during the falls. Vertical Ground Reaction Forces (VGRF) were analyzed by measuring two peaks (defined below) and their respective times. Vertical force magnitudes were normalized to 'times body weight' (TBW): a ratio between the obtained digitized peak force values and the individual digitized body weight values obtained from a 'calibration trial' before the initiation of each landing session. The first peak of force was defined as the first sudden increase in magnitude on the vertical direction transduced from the force plate in mechanical units / volt. The second peak was defined as the largest peak after touchdown. The respective times-to-peak forces were measured from the moment of contact with the platform at time 'zero'. Correlation coefficients were obtained between these variables (Tables 10a and 10b) in order to assess to extent to which they were different measures arising from the same component of force.

TABLE 10a Correlation coefficients obtained from the vertical component of ground reaction forces (Peaks and Time to Peak) in **vision** conditions.

	SUBJECTS					
Pairs	**1**	**2**	**3**	**4**	**5**	**6**
PFP-PSP	.83**	.75**	.88**	.86**	.88**	.95**
TFP-TSP	.96**	.92**	.96**	.93**	.85**	.83**
PFP-TFP	-.34	-.38	.38	.47	.62*	.59
PSP-TSP	-.39	-.45*	-.49*	-.20	-.48*	-.29

* p ≤ .05

** p ≤ .01

TABLE 10b Correlation coefficients obtained from the vertical component of ground reaction forces (Peak and Time to Peak) in **no-vision** conditions.[6]

	SUBJECTS					
Pairs	**1**	**2**	**3**	**4**	**5**	**6**
PFP-PSP	.88**	.70*	.85**	.86**	.94**	.77**
TFP-TSP	.96**	.97**	.22	.96**	.84**	.91**
PFP-TFP	-.35	.67*	.64*	.54	.59*	.03
PSP-TSP	-.49	-.40	-.44*	-.16	.55**	-.45*

* p ≤ .05

** p ≤ .01

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[6] PFP: peak of the first increase in vertical force; TFP: time to the first peak; PSP: peak of the major increase in vertical force; TSP: time to the second peak.

The correlations show high r^2 coefficients and significant probability levels between amplitude of the first peak (PFP) and amplitude of the second peak (PSP). This was also observed for their respective times to peak values (TFP and TSP). However, the correlation coefficients for the amplitude of the peaks and their respective times were relatively low and non-significant. It seems that these two measures of the same force outcome are different, and therefore they should be treated as representative of independent processes taking place after landing.

In the case of the PFP and TFP, they were not elicited in all trials, particularly in low height landings. The following histogram shows the average percentage of trials (across subjects) for each falling height in which the first peak of ground reaction forces was present.

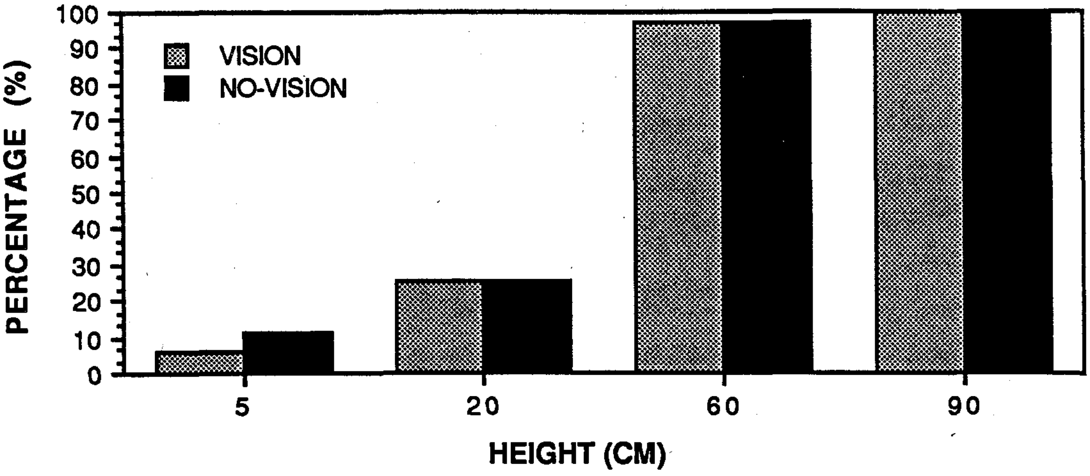


Figure 10 Histogram for the first peak of vertical ground reaction forces (percentage of trials).

6.3.2. Initial results of the vertical force analysis.

In order to evaluate to what extent collapsing over subjects was a reasonable step, a 2-way repeated measures analysis of variance (2 'conditions' x 4 'heights', PSP as the dependent variable) was separately performed for each subject (6 repeated trials). The results are shown in Table 11.

Table 11 *F values and p levels of the analysis of variance on PSP for each subject*.

SUBJ.	'CONDITIONS'	'HEIGHTS'	'INTERACTION'
1	*F*(1,4) =5.23	*F*(3,12) =61.09**	*F*(3,12) =0.81
2	*F*(1,5) =0.87	*F*(3,15) =53.09**	*F*(3,15) =3.43*
3	*F*(1,5) =1.08	*F*(3,15) =55.06**	*F*(3,15) =0.15
4	*F*(1,5) =3.63	*F*(3,15) =123.38**	*F*(3,15) =1.25
5	*F*(1,5) =0.14	*F*(3,15) =227.35**	*F*(3,15) =2.22
6	*F*(1,5) =3.17	*F*(3,15) =24.81**	*F*(3,15) =4.54*

* $\alpha \le .05$

** $\alpha \le .01$

The above results show that the effects of 'conditions' does not differ from subject to subject, neither does the 'heights' factor. Although post-hoc comparisons were not performed, it seems that the differences in peak forces from different heights are obvious at first glance, with a few exceptions in subject 1 (no-vision, 5-20 cm), subject 2 (no-vision 60-90 cm), and subject 6 (vision, 20-60 cm) as observed in the table 14a of means for each subject presented in the following section.

The interaction between the two within factors was significant only in two subjects. It was decided in light of the results obtained for the two main effects that an analysis based on values collapsed across subjects was justified.

6.3.3. Analysis of the first peak of the vertical force components.

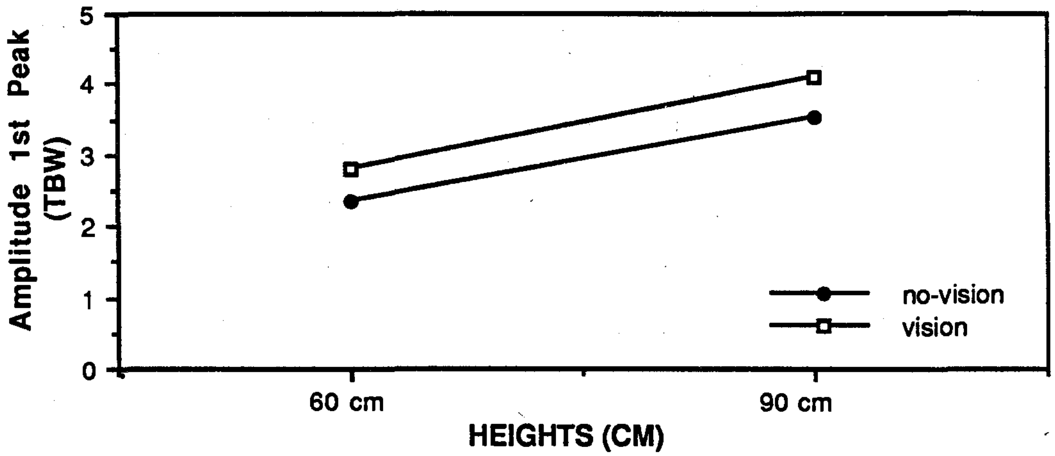
A 2-way analysis of variance (2 'conditions' x 2 'heights') with repeated measures on the two factors was carried out for each dependent variable (PFP and TFP) only in the highest landing categories. The results showed a main effect for 'conditions' with the vision condition presenting significantly higher magnitudes ($\alpha \leq .05$) when PFP was the dependent variable. The main effect for 'heights' was as expected, with the 90 cm height significantly higher than the 60 cm one, while the interaction was not significant. The results are reported in Table 12a and Table 12b, and plotted in following figure.

Table 12a Individual PFP means (in TBW), PFP means and S.D. per height of fall across subjects.

	VISION		NO-VISION	
HEIGHT	**60**	**90**	**60**	**90**
SUB.1	2.38	3.54	1.95	3.86
SUB.2	4.11	6.18	3.45	4.53
SUB.3	2.54	4.20	2.48	3.85
SUB.4	2.86	4.81	3.01	4.26
SUB.5	2.01	2.07	1.39	2.08
SUB.6	2.91	3.66	1.87	2.68
MEAN	2.80	4.08	2.36	3.54
S.D.	0.72	1.38	0.77	0.96

Table 12b Results of the analysis of variance on two conditions, and two heights of fall (PFP as the dependent variable).

MAIN EFFECTS	d.f.	F value	prob. F
Heights	3, 15	33.58	.003
Conditions	1, 5	6.57	.049
Interaction	3, 15	.09	.765



<u>Figure 11</u> Main effects for 'conditions' and 'heights' when the amplitude of the first peak was the dependent variable.

The first main effect may be explained as the result of the dependence on visual cues in order to time the response before touchdown. Blindfolded subjects diminished the risk of injury by being ready in advance, and thus they were able to dissipate the initial ground reaction forces occurring within ≤ 16 msec after touchdown (i.e., the first peak of force). A similar suggestion has been lately forwarded by Viitasalo and Aura (1987). The times to first peak found by the latter investigators were 22 msec (± 4 msec), this period being too short for the build-up of tension in the muscle. In their study, the time to first-peaks caused a deterioration in the use of the potential energy of the elastic components.

Viitasalo and Aura (1987) suggested that athletes show a pre-activity EMG build-up of tension (in 3 knee extensors recorded) in order to compensate for the insufficient time allowed for the stretch reflex system to become activated, and to resist the elongation immediately after touchdown.

It is worth noting that magnitudes of the order of 4.08 times body-weight (on average) as obtained here, may certainly be a cause of injuries, for example, in unexpected falls or as in our case when individuals unconsciously increased the risk involved by depending heavily on visual cues. Valiant and Cavanagh, 1985, reported peaks of similar magnitudes as being high impact forces (e.g., in basketball jumping performances). When considering that muscular forces may not increase enough within the time period the first peak develops, then muscular tension should build up before so that it "can provide the torques necessary for the active deceleration process of the body" (Denoth et al., 1985, p. 668). This should serve to decrease the forces exerted at the knee and the ankle joints (Smith, 1975). Careful consideration should be given to unexpected situations, since these force peak magnitudes approximate forces which may be responsible for fractures of different kinds, in different populations (e.g., femoral neck stress fractures in old people caused by vertical forces between 5-7 TBW, as found by

Griffiths et al. (1971; as cited by Greenwood and Hopkins, 1980, p.305).

The results from the second 2-way RM ANOVA (2 'conditions' x 2 'heights') with times to first peak (TFP) as the dependent variable revealed no main effects for conditions suggesting that subjects, in the absence of visual cues, succeeded in eliciting lower magnitude first peaks within similar periods of time. The main effect for 'heights' was significant. The results are shown in the Table 13a and Table 13b below, and illustrated in Figure 12.

Table 13a Individual TFP means (in msec), TFP means and S.D. per height of fall across subjects.

	VISION		**NO-VISION**	
HEIGHT	**60**	**90**	**60**	**90**
SUB.1	15	8	12	9
SUB.2	12	10	13	11
SUB.3	18	14	17	21
SUB.4	17	14	18	14
SUB.5	18	11	11	11
SUB.6	17	13	16	13
MEAN	16.17	11.67	14.50	13.17
S.D.	2.32	2.42	2.88	4.22

Table 13b Results of the analysis of variance on two conditions and two heights of fall (TFP as the dependent variable).

MAIN EFFECTS	d.f.	F value	prob. F
Heights	3, 15	16.66	.010
Conditions	1, 5	.13	.733
Interaction	3, 15	5.13	.072

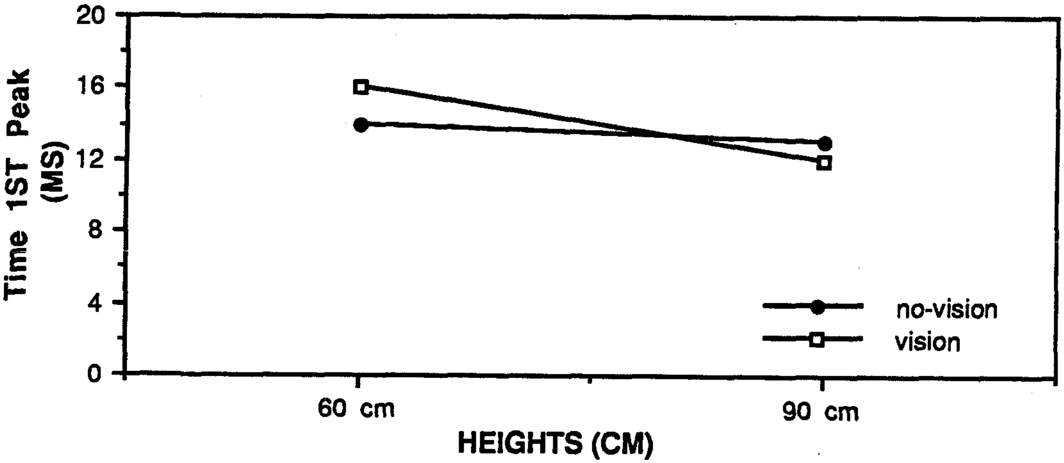


Figure 12 Main effects for 'heights' when time to first peak was the dependent variable.

6.3.4. Analysis of the second peak of vertical force components.

The second peak of force 'PSP', and the time to this peak 'TSP' were observed in all trials in the four landing height categories. Analysis of these dependent variables may be more sensitive to differences between 'conditions' and 'heights'. Accordingly, analyses of variance were performed.

The results of the first 2-way RM ANOVA (2 'conditions' x 4 'heights') (PSP as the dependent variable) showed no significant main effects for 'conditions', providing additional evidence in support of previous findings. Vision did not appear to enhance a more efficient dissipation of vertical ground reaction forces after landing than in situations in which visual guidance was occluded. These non-significant differences cannot be attributed to increased variability terms (low power of the test) since the variance was small and other effects were obtained with the same data, for example, the main effect for 'heights' which was significant as expected. Tukey (HSD) post-hoc comparisons revealed that all pair-wise comparisons were significant (at $\underline{\alpha} \leq .05$). The interaction between the two factors was not significant. Table 14a presents the individual means and S.D., Table 14b shows the results of the analysis of variance, and Table 15 presents the marginal means, and the differences for each pair.

Table 14a Individual PSP means (in TBW), 'height' means and S.D. across subjects.

	VISION				NO-VISION			
HEIGHT	**5**	**20**	**60**	**90**	**5**	**20**	**60**	**90**
SUB.1	2.49	3.20	4.18	6.46	2.37	2.74	4.79	6.54
SUB.2	1.66	2.24	3.41	5.71	1.63	2.25	3.99	4.33
SUB.3	1.96	2.92	4.26	5.39	1.85	2.78	3.91	5.00
SUB.4	1.90	2.36	3.40	4.04	1.86	2.31	3.10	3.74
SUB.5	2.37	3.14	5.64	6.51	1.68	3.20	5.28	7.21
SUB.6	1.82	3.77	3.70	6.20	1.56	2.21	4.09	5.85
MEAN	2.03	2.95	4.07	5.69	1.81	2.60	4.19	5.50
S.D.	0.33	0.58	0.84	0.91	0.26	0.40	0.75	1.39

Table 14b Results of the analysis of variance on two conditions and four heights of fall (PSP as the dependent variable).

MAIN EFFECTS	d.f.	F value	prob. F
Heights	3, 15	65.85	.001
Conditions	1, 5	3.68	.112
Interaction	3, 15	.64	.603

Table 15 Post-Hoc comparisons between PSP (in TBW) marginal means, and significance of the differences.

	HEIGHTS (CM)			
	5	**20**	**60**	**90**
Marg.Means	1.92	2.77	4.13	5.60
5	-	.85*	2.21*	3.68*
20		-	1.36*	2.83*
60			-	1.47*
90				-

*$\alpha \leq .05$

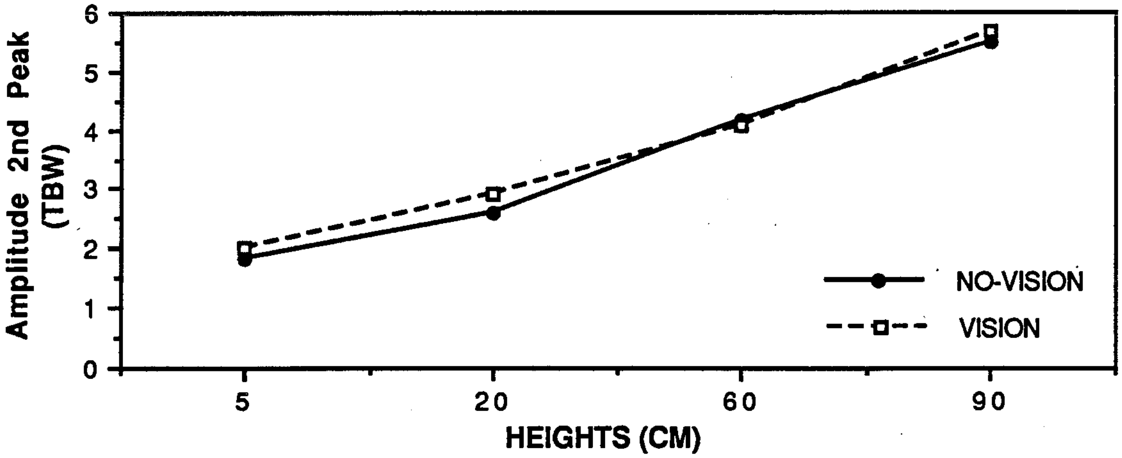


Figure 13 Main effects for 'heights' when amplitude of the second peak was the dependent variable.

The second 2-way RM ANOVA (2 'conditions' x 4 'heights') with time to second peak (TSP) as the dependent variable showed similar results. The main effect for 'conditions' was not significant, while the effects for 'heights' achieved significant levels. Post-hoc comparisons (Tukey HSD) showed that the times to peak-force for the two highest landing categories were not significantly different ($\alpha \leq .05$). The interaction was not significant either. Table 16a includes the individual means, and S.D., Table 16b presents the results for the analysis of variance, and Table 17 shows the post-hoc comparisons between marginal means and their level of significance.

Table 16a Individual TSP means (in msec), TSP means and S.D. per height of fall across subjects

	VISION				NO-VISION			
HEIGHT	**5**	**20**	**60**	**90**	**5**	**20**	**60**	**90**
SUB.1	125	101	71	49	152	97	62	46
SUB.2	98	89	60	46	177	78	59	52
SUB.3	162	106	69	57	150	102	65	47
SUB.4	93	80	59	52	95	77	66	51
SUB.5	97	80	52	43	100	75	47	41
SUB.6	102	86	48	46	114	88	59	49
MEAN	113	90	60	49	131	86	60	48
S.D.	26.63	10.89	9.06	5.04	33.06	11.37	6.86	3.98

Table 16b Results of the analysis of variance on two conditions and four heights of fall (TSP as the dependent variable).

MAIN EFFECTS	**d.f.**	**F value**	**prob. F**
Heights	3, 15	52.21	.001
Conditions	1, 5	.82	.409
Interaction	3, 15	2.28	.120

Table 17 Post-hoc comparisons between TSP (msec) marginal means and significance of the differences.

	HEIGHTS (CM)			
	90	**60**	**20**	**5**
Marg.Means	48.14	59.68	88.01	122.01
90	-	11.54	39.87*	73.87*
60		-	28.33*	34.00*
20			-	62.33*
5				-

*$\alpha \leq$ .05

The non-significant differences observed between the two highest categories of fall could be interpreted as a threshold time to dissipate the vertical thrust beyond which subjects could no longer use the articular chain to extend the time-to-peak.

The marginal means from the analysis of variance are plotted in figure 14:

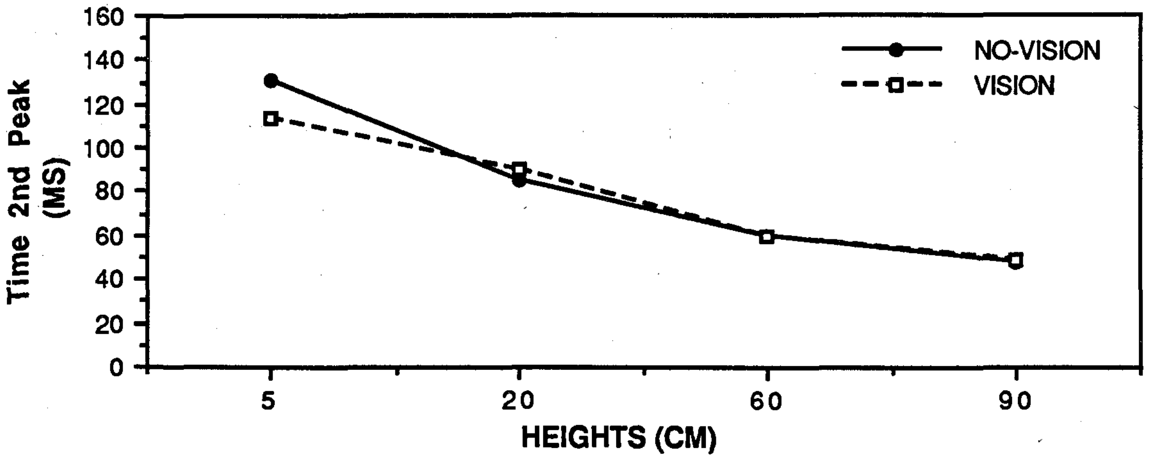


Figure 14 Main effects for 'heights' when time to the second peak was the dependent variable.

6.4. Subjects commentaries.

Surprisingly, four of the subjects reported that when they "got used to the idea of landing blindfolded" (after the first 2-3 trials), they felt that their landings were softer than they expected. Upon completion of the testing sessions, they reported that the no-vision trials "felt better" performed than those with visual guidance. On the other hand, one subject reported no difference between the two conditions, and one subject reported that he was definitively less anxious when visual cues were available.

It seems that when dependence on the visual cues were eliminated, subjects were more aware of the risks and probably prepared better for landing. Therefore, it may be suggested that cognition rather than vision, may thus play a more important role than initially assigned to it.

7. General Discussion

Human preparatory responses in different activities have been the focus of interest within diverse fields investigating motor behavior. Walking, for instance, presents alternate EMG activity in different muscle groups of the lower limbs, depending on the phase of the movement sequence (Herman et al., 1973). Relatively synchronized EMG patterns occur before actual angular displacements are observed. These are interpreted as 'pre-programmed' responses of central origin triggered by peripheral stimuli. Postural adjustments during sudden arm movements have also been interpreted as pre-programmed (Belen'kii et al., 1967; Lee, W., 1980; Lee et al., 1987; Nashner and Cordo, 1981). Experiments on landing responses have tended to focus on the latencies of onset of lower limb muscles and the voluntary phase in a general way (Melvill Jones and Watt, 1971a, b; Greenwood and Hopkins, 1976a, b). During the present investigation one of the possibilities evaluated was the existence of a particular mode of (task-specific) functional organization in response to free-falls. Some preliminary evidence can be elucidated from the results. For instance, particular muscles (the rectus femoris and the gastrocnemius) seem to be consistently active in the preparation for landing, while others (tibialis anterior, vastus lateralis, and biceps femoris) seem to be mainly activated in the post-landing period. A major difference between this study and others examining preparatory (e.g., Lee W, 1980, Nashner and Cordo, 1981) is that it is impossible to incorporate a RT paradigm in a free-fall task, since the response is triggered internally during an ongoing event (i.e., during the flight path). One hypothesized 'go' signal was the optically determined T margin value, which allows the adoption of a strategy based on the directly perceived time-to-contact (or "time to the nearest approach" as expressed by Lee and Young, 1985, p.1). This heuristic arises from the relationship between the physical world in interaction with the living organism. Thus, it takes into account various sources of information (e.g., the relationships between projections of environmental layouts at the optic array, body position in space, body proportions) in the form of invariants (e.g., the rate of change of the angles of occluding objects approaching the observers' eyes, a ratio between limb proportions and perceived height of step, or the ratio between force output and the momentum gained during the fall). If subjects were using this type of visual strategy their response would not necessarily be interpreted as pre-programmed, since the relationship between the optic variables is directly perceived and accommodates to each individual situation. Accordingly, visual cues seem to be essential to regulate adaptive responses in the free-fall task, while the time-to-collision with the ground within this mode of perception seems to be the main source of information. The importance of other measurable variables such as distance, velocity, or acceleration was regarded with skepticism in light of reported evidence. For example, for estimation of distance the findings do not seem to favor this parameter as a candidate (Gibson and Bergman, 1954; Gibson et al., 1955), and for the perception of the latter parameters of movement the evidence is rather unclear (e.g., see Rosenbaum, 1975). Subjects do not seem to take any conscious advantage of these variables (Todd, 1981), either in symbolic form, or in terms of their meaning through experiencing them. Lee (1976, 1980a) suggested that the τ heuristic may be valuable in tasks such as jumping down from heights. However, the τ variable specifying time-to-contact was not found to be a relevant source of information in the timing of the preparatory response within the flight durations used during this experiment. Moreover, the importance of the visual information during the task itself was questioned as a result of the present findings, since blindfolded subjects succeeded in reducing the impact with the ground as well as when vision was available (assessed by the vertical components of ground reaction forces).

A suggestion of late is that intermittent visual cues at specific times during the performance, for example while walking towards target lines situated at different distances, seem to be sufficient in eliciting responses as precise as when continuous visual cues are available to the performer (Laurent and Thomson, 1988). Thomson (1983) provided some evidence which led to the conclusion that visual guidance is not necessary in walking towards a pre-determined goal, since the response is dependent on certain time constraints rather than in the distance walked (distances that took less than 8 sec to complete produce accurate responses). This seemed to be controversial, since these results were not replicated in a different attempt (Elliott, 1986). More recently, Elliott (1987) failed to find support for Thomson's original suggestion of an 8 sec range of time during which a short-term visual representation of the environment is effective in substituting for the occluded visual input in walking towards a target. Elliott (1986) found no differences in error variability between locomotion periods longer or shorter than 8 seconds. Nevertheless, in tasks which last periods shorter than 2 sec (e.g., manually aiming towards a target) Elliott and Madalena (1987) suggested as plausible that visual representations are available and used when vision is eliminated, thus producing results that do not significantly differ from those when visual cues are continually available. Had the subjects during the free-fall trials in this experiment taken less than 2 sec to prepare, to release themselves, and to land, then Elliott and Madalena's findings would be supported by the evidence presented here, since their results showed that only after periods equal or longer than 2 sec. the error greatly increased (Elliott and Madalena, 1987). However, the lapse of time from the moment the subjects wore the goggles, until the end of the landing was considerably longer (5-15 sec approximately) than the 2 sec period of effective visual representation reported by Elliott and Madalena (1987), and even longer than the 8 sec time-window reported by Thomson (1983). Still the absence of visual guidance within these long time lapses did not cause a detriment in the performance.

It may be speculated that blindfolded performers adjusted the preparatory landing response based on a visual representation of the height of fall acquired before the initiation of the trial within time ranges longer than those reported in the literature.

The hypothesis of internal representations of environmental cues contradicts some of the basic postulates of the direct perception approach, and thus, it also argues against the model proposed by Lee (1980a), at least for the landing task. The τ heuristic, nonetheless, has been reported to be effective in a wide variety of tasks, mainly when τ is greater than certain values. Higher landing heights may certainly approach higher τ values, but they are not only difficult for experimental purposes, but also they are seldom observed in real life situations. If so, what strategy may be used in skills that require precise timing, and present low time-to-contact values? (e.g., in catching a moving object, or in hitting a ball with a racket). There is evidence in fact, that in catching moving objects, the T heuristic is not used by infants (von Hofsten, 1983). Rather, babies seem to use a strategy based on synchronization of the time of initiation of the hand movement and the object, while they follow its direction, i.e., matching the velocity profile of the moving object. As expressed by von Hofsten (1987) visual human perception may have developed in a highly specialized way. Thus, there may be different modes of action-perception to meet the time constraints encountered by human or animal subjects in different dynamic contexts. Vision appears to play a significant role in animal actions, mainly during those actions which require an appreciation of the time-to-contact with surfaces (Lee and Reddish, 1981; Wagner, 1982; Wehrhahn et al., 1981). In contrast, in the present landing experiment, self-released performers with visual cues available did not show any advantage in dissipating the shock at collision with the ground, nor did they apparently use a different preparatory strategy, than when they were blindfolded. It is worth mentioning, however, that the tuning function of visual perception may be evident if the visually guided and blindfolded landings took place after 'unexpected release' conditions. This is suggested as the next step in a series of experiments on the topic.

The otolith organs may have also played a role as detectors of the initiation of downward vertical motion of the head. Greenwood and Hopkins (1976b) have shown that these vestibular structures may be responsible for reflexive EMG patterns observed during the flight path. In addition, other kinesthetic sources may be involved in the perception of changes in acceleration from 1 g to 0 g. Fluctuations in the pressure exerted by internal body structures and pressure on the skin, may have also indicated to the subjects when the fall was actually initiated. Individuals seem to be sensitive to these sources of information, for example, in parabolic flight maneuvers (Lackner, 1985). A conglomerate of environmental information reaching different perceptual systems simultaneously seem to be unquestionable in this task. When one of these perceptual modes fails to detect information or regards it as redundant, other means seem to compensate in order to generate the appropriately timed action. In this study, the strategy which appeared to be used by subjects in either vision or no-vision condition, did not take into account the optically specified time to the nearest approach to the ground. Analysis of the vertical ground reaction forces confirmed that vision does not help in dissipation of the impact cause by the vertical momentum gained during the fall. Greenwood and Hopkins (1976b) and Dietz and Noth (1978) early pointed out that differences in the preparatory patterns of both conditions were not evident in their EMG recordings. This similarity in timing led to the interpretation that preparatory response during free-falls asre dependent on "knowledge of the height, and not necessarily on continuous visual input" (as cited by Prochazka, 1980, p. 290). However, this interpretation is not supported by other findings. Dyhre-Poulsen et al. (1980) showed that in monkeys the latency of onset of EMG activity in preparation to land seems to be guided by vision. These authors unexpectedly added a 'paper ring' between the landing platform and the jumping device, thus causing a change in the preparatory EMG onset only after the animal appeared to be deceived by landing beyond what was visually perceived as the landing surface.

Early in this paper, it was mentioned that Greenwood and Hopkins (1976a) interpreted the timing of the second burst of activity (i.e., the voluntary response) as being dependent on the height of fall. However, this is not supported by the results of this experiment, since the activity was related to temporal factors. Also, knowledge of the height of fall in absolute terms may play a limited role in the preparation to land, especially if this was related to the moment of release, as indicated by our results. Knowledge of the type of landing place, nonetheless, elicit different EMG patterns. Fukuda et al. (1987) for example, reported that stiff vs. softer landing surfaces caused a change in the amplitude and the onset time of electrical activity in the gastrocnemius and the tibialis anterior, even in landings from 8-18 mm height. Similar, but more specific findings were reported by Gollhofer (1987). Differences in landing surfaces were suggested to be responsible for onset and steepness of rise in pre-activation of the medial gastrocnemius in 25 cm falls (at least these differences were observed when the subjects landed onto a mini-tramp as opposed to other surfaces, including a force plate).

In fact, none of these studies seem to appreciate that humans as much as other animals, might have an inherent faculty to estimate durations, i.e., the flow of time between events. Subjects in this study seem to have estimated an approximate duration of the flight for each height of fall (assumed to occur after the first 2-3 practice trials). We have demonstrated elsewhere (Liebermann, Raz, and Dickinson, 1988, in press) that subjects are capable of estimating movement duration even without intention to do so (i.e., when they were instructed to focus their attention on the spatial information of the movement pattern). Accordingly, subjects initiated their actions during the flight, at a relatively constant time after they perceived the initiation of the fall. This is the case as evidenced from the results of the best-fitting curves for each subject (figure 7a-7f), which yielded generally higher *r* coefficients when the linear model was superimposed on the empirical results. The linear best-fitting model was confirmed, at least partially, from the regression analysis performed on the same data. For individual cases and pooled data of the gastrocnemius the latter procedure showed the predominance of the linear trend, while in the case of the rectus femoris muscle the results slightly differed (nevertheless, as an argument 'by default' the negatively accelerated model expected from the τ heuristic was not evident; the opposite trend (an exponential growth) was observed for this muscle). The optic τ variable did not appear to be relevant. Both, blindfolded and visually guided landings, did not seem to be different in terms of the strategy used in the preparation to land, and thus, subjects did not differ either in their ability to cushion the landing.

8. Summary and conclusions

This study examined whether or not the preparatory landing response in voluntarily self-release falls is guided mainly by visual information. The results of this experiment indicate that vision is not essential in guiding the action.

Five main questions were asked based on the assumption that the interaction between the environment and the performer elicit adaptive actions when the stimuli afforded a change in their relationship. Visual perception was considered as the central source of information responsible for timing the adaptive landing responses, assuming that the free-fall was 'afforded' by our subjects as a task in which collision with the ground requires an immediate and precise adaptive response to avoid injuries. The action was hypothezised to be guided by the optic 'system-scaled' τ variable, expected to produce a well timed action, and to evidence that the human system behaves as an "optimizer". The results of the experiment are summarized as follows:

1) Is the τ strategy (Lee, 1974,1976,1980) used in timing the preparation to land?

Under the present experimental conditions this strategy did not appear to be used in voluntarily self-initiated free-falls from heights covering a wide range of those usually observed in real life situations.

2) Is the strategy adopted by the blindfolded performers related to the moment of initiation of the fall rather than to the moment of landing?

This seems to be the case not only for the no-vision landings but also when vision was available: the results provided evidence for a linear increment in perceived time-to-contact with increases in the flight time. This strategy may not be 'optimal', since subjects started preparing earlier than needed during the flight with increases in the height of fall. Nonetheless, it allowed safe landings in either visual condition.

3) Does vision compared to no-vision conditions enhance the ability to dissipate the vertical ground reaction forces at collision with the ground?

Visually guided landings elicited higher magnitude first peaks (i.e., PFP, which is a "passive phase") within similar times periods (TFP) compared to blindfold landings, while no differences were found between conditions in the magnitude of the second peak (PSP) or in its respective time to peak (TSP).

(i.e., the "active phase"). Therefore, it is concluded that vision did not enhance softer landings. Rather, over-reliance on visual guidance appeared to cause a detriment in the ability to dissipate the initial vertical ground reaction forces, since these peaks occurred in such short time lapses that muscular tension could not possibly be developed. Blindfolded subjects prepared in advance, and thus reduced the magnitudes of the first peak.

4) Do different heights of fall or visual conditions have any effect on the activity before the initiation of the fall?

Both visual conditions showed pre-release EMG activity in the rectus femoris muscle. However, blindfolded performers exhibited a higher proportion of active trials confirming that they were preparing in advance. On the other hand, different heights of fall did not have any effect on early onset of activity. This finding led to a rejection of the hypothesis stating that in very low landing heights subjects would compensate for the short time available for preparation, by initiating the action before release, and hence avoiding a jolt at touchdown.

5) Is there any evidence that confirms the involvement of startle reflexive activity in no-vision trials, as reported by Greenwood and Hopkins (1976b) during unexpected fall? If so, what are the effects of different heights of fall or visual conditions?

It is not possible to confirm or to dismiss a co-operative interaction between startle reflexive mechanisms and voluntary activity. The results showed that an unrelated landing muscle (frontalis) was activated in a large proportion of trials during the flight, significantly, when vision was occluded. But this activation was unrelated to the presence of 'startle reflexes' (first burst of EMG activity at a latency of onset of 75 msec) in other muscle groups. Therefore, changes in the proportion of trials in which the frontalis was activated seems to be representative of distinct levels of arousal caused by different visual conditions. Furthermore, very low heights did not elicit this startle activity. It may be speculated that subjects were more 'alert', particularly, in no-vision conditions and in landings from heights of fall beyond 20 cm, and this state may be have co-operated with the voluntary preparation to land.

Cognitive factors appear to play an important role in the organization of the action. Subjects may have acquired a visual representation of the environment prior to the application of the blindfold, and this could probably be used in adjusting the response. Therefore, it would be interesting to assess this particular hypothesis in future investigations, by an independent groups design in which some subjects are kept naive of the landing place prior the initiation of the experimental session, while subjects in the second group will be allowed to visually obtain environmental cues.

In spite of the present results, the importance of the visual strategies should not be categorically dismissed in this task. Unexpected free-falls may certainly show different outcomes, and may be the cause of significant increases in vertical forces. Changes in the patterns of foot pressure distribution are attributed to landings from unexpected falls (Hennig and Cavanagh, 1987). Therefore, it may be predicted that the preparatory landing activity may differ between expected and unexpected falls.

In such cases the role of the visual system may be called upon, perhaps in order to adopt the T strategy debated throughout this paper.

References

Belen'kii, V. Y., Gurfinkel, V. S., and Pal'tsev, Y. I.(1967). Elements of control of voluntary movements. Biofizika, 12, pp. 135-141.

Bernstein, N. (1984 d). Some emergent problems of the regulation of motor acts. In Whiting, H. T. A. (Ed.). Human Motor Actions. Bernstein Reassessed. Amsterdam: Elsevier Publishing Company (North-Holland).

Coren, S., Porac, C., and Ward, L. M. (1979). Sensation and Perception. N. Y.: Academic Press.

Craik, R. L., Cozzens, B. A., and Freedman, W. (1982). The role of sensory conflict on stair descendent performance in humans. Experimental Brain Research, 45, pp. 399-409.

Delagi, E. F.; Perotto, A.; Iazzetti, J.; and Morrison, D. (1975). Anatomic Guide for the Electromyographer, Springfield, Illi : Charles C. Thomas, Pub.

Denoth, J., Gruber, K., Ruder, H., and Keppler, M. (1985). Forces and torques during sports activities with high accelerations. In Perren, S. M., and Schneider, E. (Eds.). Biomechanics: current interdisciplinary research. Martinus Nijhoff Publishers: Dordrecht, The Netherlands.

Dietz, V., and Noth, J. (1978). Pre-innervation and stretch responses of the triceps brachii in man falling with and without visual control. Brain Research, 142, pp. 576-579.

Dyhre-Poulsen, P., Mosfeldt Laursen, A., Jahnsen, H., and Djorup, A. (1980). Programmed and reflex activity in monkeys landing from a leap. In Desmedt, J. E. (Ed.). Spinal and supraspinal mechanisms of voluntary motor control and locomotion. Progress in clinical neurophysiology, 8, pp. 323-329. Basel: Karger.

Easton, T. A. (1978). Coordinative structures -the basis for a motor program. In Landers, D., and Christina, R. (Eds.). Psychology of motor behavior and sport, pp. 63-81. Champaign, Illi.: Human Kinetics Publishers.

Elliott, D. (1986). Continuous visual information may be important after all: A failure to replicate Thomson (1983). Journal of Experimental Psychology: Human Perception and Performance, 12 , pp. 388-391.

Elliott, D. (1987). The influence of walking speed and prior practice on locomotor distance estimation. Journal of Motor Behavior, 19 (4), pp. 476-485.

Elliott, D., and Madalena, J. (1987). The influence of premovement visual information on manual aiming. Quaterly Journal of Experimental Psychology, 39A, pp. 541-559.

Evarts, E. V. (1985). Transcortical reflexes: their properties and functional significance. In Goodwin, A. W., and Darian-Smith, I. (Eds.). Hand Function and Neocortex. Experimental Brain Research, suppl. 10. Heidelberg: Springer-Verlag Berlin.

Fetz, E. E., Finocchio, D. V., Baker, M. A., and Soso, M. J. (1980). Sensory and motor responses of precentral cortex cells during comparable passive and active joint movements. Journal of Neurophysiology, 42, pp. 1070-1089.

Freedman, W., Wannstedt, G., and Herman, R. (1976). EMG patterns and forces developed during step-down. American Journal of Physical Medicine, 55 (6), pp. 275-290.

Fukuda, H., Miyashita, M., and Fukuoka, M. (1987). Unconscious control of impact force during landing. In Jonsson, B. (Ed.). Biomechanics X-A, pp. 301-305. Champaign, Illi: Human Kinetic Publishers.

Gibson, E. J., and Bergman, R. (1954). The effect of training on absolute estimation of distance over the ground. Journal of Experimental Psychology, 48, pp. 473-482.

Gibson, E. J., Bergman, R., and Purdy, J. (1955). The effect of prior training with a scale of distance on absolute and relative judgements of distance over the ground. Journal of Experimental Psychology, 50, pp. 97-110

Gibson, J. J. (1950). The perception of the visual world. Boston: Houghton Mifflin.

Gibson, J. J. (1966). The senses considered as perceptual systems. Boston: Houghton Mifflin.

Gibson, J. J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin.

Gollhofer, A. (1987). Innervation characteristics of the m. gastrocnemius during landing on different surfaces. In Jonsson, B. (Ed.). Biomechanics X-B, pp. 701-706. Champaign, Illi: Human Kinetic Publishers.

Granit, R. (1973). Demand and accomplishment in voluntary movement. In Stein, R. B., Pearson, K. G., Smith, R. S., and Redford, J. B. (Eds.). Control of posture and locomotion, pp. 3-18. N.Y.: Plenum Press.

Greenwood, R., and Hopkins, A. (1974). Muscle activity in the falling man. Journal of Physiology (London), 241, pp. 26-27.

Greenwood, R., and Hopkins, A. (1976 a). Muscle responses during sudden falls in man. Journal of Physiology (London), 254, pp. 507-518.

Greenwood, R., and Hopkins, A. (1976 b). Landing from an unexpected fall and a voluntary step. Brain, 99, pp. 375-386.

Greenwood, R., and Hopkins, A. (1977). Monosynaptic reflexes in falling man. Journal of Neurology, Neurosurgery, and Psychiatry, 40, pp. 448-454.

Greenwood, R., and Hopkins, A. (1980). Motor control during stepping and falling in man. In Desmedt, J. E.(Ed.). Spinal and supraspinal mechanisms of voluntary motor control and locomotion. Progress in Clinical Neurophysiology, 8, pp. 294-309. Basel: Karger.

Gurnee, H. (1934). Thresholds of vertical movement of the body. Journal of Experimental Psychology, 17, pp. 271-285.

Hay, J. G. (1988). Approach strategies in the long jump. International Journal of Sport Biomechanics, 4, pp. 114-129.

Hennig, E. M., and Cavanagh, P. R. (1987). Pressure distribution under impacting human foot. In Jonsson, B. (Ed.). Biomechanics X-A, pp. 375-380. Champaign, Illi: Human Kinetic Publishers.

Herman, R., Cook, T., Cozzens, B., and Freedman, W. (1973). Control of postural reactions in man: the initiation of gait. In Stein, R. B., Pearson, K. G., Smith, R. S., and Redford, J. B. (Eds.). Control of posture and locomotion, pp.363-338. N.Y.: Plenum Press.

Hofsten, C. von (1983). Catching skills in infancy. Journal of Experimental Psychology: Human Perception and Performance, 9 (1), pp. 75-85.

Hofsten, C. von (1987). Catching. In Heuer, H. , and Sanders, A. F. (Eds.). Perspectives on perception and action. N.J.: Lea Publishers.

Hofsten, C. von, and Lee, D. N. (1985). Dialogue on perception and action. In Warren, W. H., and Shaw, R. E. (Eds.). Persistence and Change. Proceedings of the first international conference on event perception. N.J.: LEA Publishers.

Johansson, G. (1973). Monocular movement parallax and the near-space perception. Perception, 2, pp. 135-146.

Johansson, G., von Hofsten, C., and Jansson, G. (1980). Direct perception and perceptual processes. In Ullman, S. Against Direct Perception. The Behavioral and Brain Sciences, 3, pp. 388.

Jones, R. K., and Pick, A. D. (1980). On the nature of information in behalf of direct perception. In Ullman, S. Against Direct Perception. The Behavioral and Brain Sciences, 3, pp. 388-389.

Kandel, E. R., and Schwartz, J. H. (1985). Principles of neural science. (2nd. Ed.). N.Y.: Elsevier Science Publishers B. V.

Kelso, J. A. S., Holt, K. G., Kugler, P. N., and Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: II. Empirical lines of convergence. In Stelmach, G. E., and Requin, J. (Eds.). Tutorials in Motor Behavior. Amsterdam: North-Holland Publishing Company.

Kelso, J. A. S., Holt, K. G., Rubin, P., and Kugler, P. N.(1981). Patterns of Human Interlimb Coordination Emerge from the Properties of Non-Linear, Limit Cycle Oscillatory Processes: Theory and Data. Journal of Motor Behavior, 13 (4), pp. 226-261.

Kugler, P. N., and Turvey, M. T. (1987). Information, Natural Law, and the Self-assembly of Rhythmic Movement. Hillsdale, N. J.: L.E.A., Pub.

Kugler, P. N., Kelso, J. A. S., Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In Stelmach, G. E., and Requin, J. (Eds.). Tutorials in Motor Behavior. Amsterdam: North-Holland Publishing Company.

Lackner, J. R. (1985). Human sensory-motor adaption to the terrestrial force environment. In Ingle, D.J., Jeannerod, M., and Lee, D. N. (Eds.). Brain mechanisms and spatial vision, pp. 175-209. Dordrecht, The Netherlands: Martinus Nijhoff Publishers.

Lacour, M., Xerri, C., and Hugon, M. (1978). Muscle responses and monosynaptic reflexes in falling monkey. Role of the vestibular system. Journal of Physiology (Paris), 74, pp. 427-438.

Laurent, M., and Thomson, J. A. (1988). The rôle of visual information in control of a constrained locomotor task. Journal of Motor Behavior, 20 (1), pp. 17-37.

Lee, D. N. (1974). Visual information during locomotion. In MacLeod, R. B., and Pick, H. (Eds.). Perception: Essays in honor of James Gibson. Ithaca, N.Y.: Cornell University Press.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. Perception, 5, pp. 437-459.

Lee, D. N. (1980a). Visuo-motor coordination in space-time. In Stelmach, G. E., and Requin, J. (Eds.). Tutorials in Motor Behavior. Amsterdam: North-Holland Publishing Company.

Lee, D. N. (1980b). The optic flow field: the foundation of vision. Philosophical Transactions of the Royal Society of London, 290, pp. 169-179.

Lee, D. N., and Reddish, P. E. (1981). Plummeting gannets: a paradigm of ecological optics. Nature, 293, pp. 293-294.

Lee, D. N., and Thomson, J. A. (1982). Vision in action: The control of locomotion. In Ingle, D. J., Goodale, M. A., and Mansfield, R. J. W. (Eds.). Analysis of visual behavior. Massachussets: M.I.T. Press.

Lee, D. N., and Young, D. S (1985). Visual timing of interceptive action. In Jeannerod, M., and Lee, D. N.(Eds.). Brain Mechanisms and Spatial Vision. Dordrecht, The Netherlands: Martinus Nijhoff Publishers.

Lee, D. N., and Young, D. S, and McLaughlin, C. M. (1984). A roadside simulation of road crossing for children. Ergonomics, 27, pp. 1271-1281.

Lee, D. N., and Young, D. S. (1986). Gearing action to the environment. Experimental Brain Research Series, Vol.15, Heidelberg, Springer-Verlag.

Lee, D. N., Lishman, J. R., and Thomson, J. A. (1982). Regulation of gait in long jumping. Journal of Experimental Psychology: Human Perception and Performance, 8 (3), pp. 448-459.

Lee, D. N., Lough F., and Lough S. (1984). Activating the perceptuo-motor system in hemiparesis. Journal of Physiology, 349, p. 28P.

Lee, W. A. (1980). Anticipatory control of postural and task muscles during rapid arm flexion. Journal of Motor Behavior, 12 (3), pp. 185-196.

Lee, W. A. (1984). Neuromotor synergies as a basis for coordinated intentional action. Journal of Motor Behavior, 16 (2), pp. 135-170.

Lee, W. A., Buchanan, T. S., and Rogers, M. W. (1987). Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. Experimental Brain Research, 66, pp. 257-270.

Liebermann, D. G., Raz, T., and Dickinson, J. (1988, in press). On intentional and incidental learning and estimation of temporal and spatial information. Journal of Human Movement Studies.

Malcolm, R., and Melvill Jones, G. (1974). Erroneous perception of vertical motion by humans seated in the upright position. Acta Otolaryngologica, 77, pp. 274-283.

Mark, L. S., and Vogele, D. (1987). A Biodynamic Basis for Perceived Categories of Action: A Study of Sitting and Stair Climbing. Journal of Motor Behavior, 19 (3), pp. 367-384.

Matthews, B. H. C. (1956). Tendon reflexes in free fall. Proceedings of the Physiological Society, 20-21, pp. 31P-32P.

Matthews, Sir B., and Whiteside, T. C. D. (1960). Tendon reflexes in free fall. Proceedings of the Royal Society of London, 153, pp. 195-204.

Melvill Jones, G. (1973). Is there a vestibulo-spinal reflex contribution to running ?. Advances in Oto-Rhino-Laryngology, 19, pp. 128-133.

Melvill Jones, G., and Watt, D. G. D. (1971 a). Observations on the control of stepping and hopping movements in man. Journal of Physiology (London), 219, pp. 709-727.

Melvill Jones, G., and Watt, D. G. D. (1971 b). Muscle control of landing from unexpected falls in man. Journal of Physiology (London), 219, pp. 729-737.

Melvill Jones, G., and Watt, D. G. D., and Rossignol, S. (1973). In Stein, R. B., Pearson, K. G., Smith, S. R., and Redford, J. B. (Eds.). Control of posture and locomotion. N.Y.: Plenum Press.

Melvill Jones, G., and Young, L. R. (1978). Subjective detection of vertical acceleration: a velocity-dependent response ?. Acta Otolaryngologica, 85, pp. 45-53.

Michaels, C. F., and Carello, C. (1981). Direct Perception. Englewood Cliffs, N.J.: Prentice-Hall.

Nashner, L. M., and Cordo, P. J.(1981). Relation of automatic postural responses among leg muscles during stance. Experimental Brain Research, 30, pp. 13-24.

Prochazka, A. (1980). Muscle spindle activity during walking and during free fall. In Desmedt, J. E. (Ed.). Spinal and supraspinal mechanisms of voluntary motor control and locomotion. Progress in clinical neurophysiology, 8, pp. 282-293. Basel: Karger.

Reed, E., and Jones, R. (1982). Selected essays of James J. Gibson. Hillsdale, N.J.: LEA Publishers.

Rosenbaum, D. A. (1975). Perception and extrapolation of velocity and acceleration. Journal of Experimental Psychology: Human Perception and Performance, 1 (4), pp. 395-403.

Schiff, W., and Detwiler, M. L. (1979). Information used in judging impending collision. Perception, 8, pp. 647-658.

Smith, A. J. (1975). Estimates of muscle and joint forces at the knee and ankle during a jumping activity. Journal of Human Movement Studies, 1, pp. 78-86.

Spain, J. D. (1982). Basic Microcomputer Models in Biology. London: Addison-Wesley Publishing Company.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? Journal of Experimental Psychology: Human Perception and Performance, 9 (3), pp. 427-443.

Todd, J. T. (1981). Visual information about moving objects. Journal of Experimental Psychology: Human Perception and Performance, 7 (4), pp. 795-810.

Turvey, M. T. (1974). A note on the relation between action and perception. In Wade, M., and Martens, R. (Eds.). Psychology of motor behavior and sports, Urbana, Illi.: Human Kinetic Publishers.

Turvey, M. T. (1977). Preliminaries to a Theory of Action with Reference to Vision. In Shaw, R., and Bransford, J. (Eds.). Perceiving, acting, and knowing. Toward an Ecological Psychology. Hillsdale, N. J.: LEA Pub.

Turvey, M. T., and Carello, C. (1986). The ecological approach to perceiving-acting: a pictorial essay. Acta Psychologica, 63, pp. 133-155.

Turvey, M. T., and Kugler, P. N. (1984). An ecological approach to perception and action. In Whiting, H. T. A. (Ed.). Human Motor Actions. Bernstein Reassessed. Amsterdam: Elsevier Publishing Company (North-Holland).

Valiant, G. A., and Cavanagh, P. R. (1985). A study of landing from jumps: implications for the design of a basketball shoe. In Winter, D., Norman, R., Wells, R., Hayes, K. and Patla, A. (Eds.). Biomechanics IX-B. Champaign, Illi.: Human Kinetics Publisher.

Vidal, P. P., Lacour, M., and Berthoz, A. (1979). Contribution of vision to muscle responses in monkey during free-fall: visual stabilization decreases vestibular-dependent responses. Experimental Brain Research, 37, pp. 241-252.

Viitasalo, J. T., and Aura, O. (1987). Myoelectrical activity of the leg extensor musculature before ground contact in jumping. In Jonsson, B. (Ed.). Biomechanics X-B, pp. 695-699. Champaign, Illi: Human Kinetic Publishers.

Wagner, H. (1982). Flow-field variables trigger landing in flies. Nature, 297, pp. 14-15.

Walter, Ch. B. (1984). Temporal quantification of electromyography with reference to motor control research. Journal of Human Movement Science, 3, pp. 155-162.

Warren, W. H. (1984). Perceiving Affordances: Visual Guidance of Stair Climbing. Journal of Experimental Psychology: Human Perception and Performance, 10 (5), pp. 683-703.

Warren, W. H., and Kelso, J. A. S. (1985). Work group on Perception and Action. In Warren, W. H., and Shaw, R. E. (Eds.). Persistence and Change. Proceedings of the First International Conference on Event Perception. Hillsdale, N. J.: LEA, Pub.

Warren , W. H., Young, D. S., and Lee, D. N. (1986). Visual control of step length during running over irregular terrain. Journal of Experimental Psychology: Human Perception and Performance, 12 (3), pp. 259-266.

Watt, D. G. D. (1976). Responses of cats to sudden falls: an otolith-originating reflex assisting landing. Journal of Neurophysiology, 39 (2), pp. 257-265.

Watt, D. G. D. (1981a). Effect of vertical linear acceleration on H-reflex in decerebrate cat. I. Transient Stimuli. Journal of Neurophysiology, 45 (4), pp. 644-655.

Watt, D. G. D. (1981b). Effect of vertical linear acceleration on H-reflex in decerebrate cat. II. Sinusoidal Stimuli. Journal of Neurophysiology, 45 (4), pp. 656-666.

Watt, D. G. D., Money, K. E., and Tomi, L. M. (1986). M.I.T./ Canadian vestibular experiments on the spacelab-1 mission: 3. Effects of prolonged weightlessness on a human otolith-spinal reflex. Experimental Brain Research, 64, pp. 308-315.

Wehrhahn, C., Hansen, K., and Zanker, J. (1981). Is the landing response of the housefly (musca) driven by motion of a flow field ?. Biological Cybernetics, 41, pp. 91-99.

Wicke, R. W., and Oman, C. M. (1982). Visual and graviceptive influences on lower leg EMG activity in humans during brief falls. Experimental Brain Research, 46, pp. 324-330.

Appendix A. Differentiation procedures for the equations presented in section 3.5.

Equation (2):

$Z(t) / R = 1 / r(t)$, Z and r are time dependent,

then $Z / t = V$; and $r / t = v$

$Z / r = V / v$, and thus $Z / R * r / Z = 1 / r * v / V$.

Eliminating R we obtain $Z / R * R / V = 1 / r * r^2 / v$, which results in $Z / V = r / v$, i.e., $Z(t) / V(t) = \tau_{(t)}$, at constant approaching velocity.

Equation (3):

Under accelerating conditions, however,

$$\tau_{(t)} = [Z_{(0)} - (A \cdot t^2 / 2)] / A \cdot t$$
$$= (1 / t)\ [(Z_{(0)} / A) - (t^2 / 2)]$$
$$= (1 / 2 \cdot t)\ [(2 \cdot Z_{(0)} / A) - t^2]$$

Having $t_d = [2 \cdot Z_{(0)} / A]^{1/2}$,

then $Z_{(0)} = (1 / 2)\ A \cdot t_d^2 = A \cdot t_d^2 / 2$.

Replacing $Z_{(0)}$ results in:

$$\tau_{(t)} = (1 / 2 \cdot t)\ [\ ((2 \cdot (1 / 2)\ A \cdot t_d^2) / A) - t^2]$$
$$= [t_d^2 - t^2] / 2 \cdot t$$

Equation (4):

$$t^2 / 2 \cdot t = t_d^2 / (2 \cdot t - \tau_{(t)})$$

$$t^2 = t_d^2 - 2 \cdot t \cdot \tau_{(t)}$$

$$t_d^2 = t^2 + 2 \cdot t \cdot \tau_{(t)} + \tau_{(t)}^2 - \tau_{(t)}^2$$

$$t_d^2 + \tau_{(t)}^2 = (t + \tau_{(t)})^2$$

$$t = [t_d^2 + \tau_{(t)}^2]^{1/2} - \tau_{(t)}$$

time-to-contact $t_c = td - t$

$$= \tau_{(t)} + t_d - [t_d^2 + \tau_{(t)}^2]^{1/2}$$

Appendix B. SIMON FRASER UNIVERSITY Information sheet for subjects

Title of the project: A direct approach to landing in humans: implications of the time-to-contact variable as a modulator of the voluntary timing response during free-falls.

This experiment intends to examine the role of the visual system in obtaining the necessary information to respond to environmental stimuli, in this case a fall from a height. The test consists of a total of 80 free-fall trials from heights ranging from 5 cm to 95 cm. Muscle electrical activity (EMG) will be recorded during the performance via surface electrodes at six different muscle sites. This technique is widely used and considered safe. Preventive measures are taken as with the use of any electrical device.

You will be asked to complete a medical release form signed by you. Upon full agreement, you will perform landing trials in two conditions. These are defined as either the 'vision' or the 'no-vision' experimental conditions (note that the latter will perform trials wearing goggles which eliminate visual cues).

During the testing sessions you will suspend yourself over the landing site by grasping an overhead bar. The height will be determined by the experimenter. You initiate the fall when you are ready simply by letting go of the overhead bar. In the no-vision condition you may observe the height of the fall prior to being blindfolded. The landings will be performed barefooted, and you will be required to fixate your glance within a bandwith of 30-50 cm wide delimited by two landmarks. There will be a resting period between conditions, or between trials if you consider that as appropriate. The falls may be likened, at the more extreme heights, to jumping of an elevated table. This is the type of activity which children perform frequently. As long as you exhibit some care it should be entirely safe. **Please note that there is some risk of physical damage caused by inappropriate landing skills.** Practice landings will take place prior the start of the testing session in order to ensure you develop a safe landing skill. The practice trials are also provided to standardize the landing technique. A landing matt designed to cushion your fall will be placed over the landing site. The entire session will take approximately 3 hours. The experiment may be terminated at any time upon your request. All results and questionnaires will remain confidential. A synopsis of the study findings will be available on request, from myself, upon completion of the investigation. If you have any questions please, do not hesitate to ask. Thank you in advance for your co-operation.

Dario Liebermann

INFORMED CONSENT BY SUBJECTS TO PARTICIPATE IN A RESEARCH PROJECT OR EXPERIMENT

Note: The University and those conducting this project subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of subjects. This form and the information it contains are given to you for your own protection and full understanding of the procedures, risks and benefits involved. Your signature on this form will signify that you have received the document described below regarding this project, that you have received an adequate opportunity to consider the information in the document, and that you voluntarily agree to participate in the project.

Having been asked by Dario G. Liebermann of the

Kinesiology ~~Faculty~~/School/~~Department~~ of Simon Fraser University to participate in a research project experiment, I have read the procedures specified in the document entitled:

A direct approach to landing in humans: Implications of the time-to-contact.

I understand the procedures to be used on this experiment and the personal risks to me in taking part.

I understand that I may withdraw my participation in this experiment at any time.

I also understand that I may register any complaint I might have about the experiment with the chief researcher named above or with

Dr. E. Banister,

~~Dean~~/Director/~~Chairman~~ of School of Kinesiology Simon Fraser University.

Copies of the results of this study, upon its completion, may be obtained by contacting:

D. Liebermann, School of Kinesiology, SFU

I agree to participate by initiating a number of free-falls from an overhead bar while EMG activity is monitored. Falls will be berformed either with or without vision.

(state what the subject will do)

as described in the document referred to above, during the period: March 21 - August 31, 1988.

at laboratories in the Department of Kinesiology, SFU

(place where procedures will be carried out)

NAME (Please print): ____________________

ADDRESS: ____________________

____

SIGNATURE: ____________________ WITNESS: ____________________

DATE: ____________________

Once signed, a copy of this consent form and a subject feedback form should be provided to you.

Appendix C. **Health Related Questionnaire**

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)*
A Self-administered Questionnaire for Adults

PAR Q & YOU

PAR-Q is designed to help you help yourself. Many health benefits are associated with regular exercise, and the completion of PAR-Q is a sensible first step to take if you are planning to increase the amount of physical activity in your life.

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them.

Common sense is your best guide in answering these few questions. Please read them carefully and check the ☑ YES or NO opposite the question if it applies to you.

YES NO

☐ ☐ 1. Has your doctor ever said you have heart trouble?

☐ ☐ 2. Do you frequently have pains in your heart and chest?

☐ ☐ 3. Do you often feel faint or have spells of severe dizziness?

☐ ☐ 4 Has a doctor ever said your blood pressure was too high?

☐ ☐ 5. Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by exercise, or might be made worse with exercise?

☐ ☐ 6. Is there a good physical reason not mentioned here why you should not follow an activity program even if you wanted to?

☐ ☐ 7. Are you over age 65 and not accustomed to vigorous exercise?

If You Answered

YES to one or more questions

If you have not recently done so, consult with your personal physician by telephone or in person BEFORE increasing your physical activity and/or taking a fitness test. Tell him what questions you answered YES on PAR-Q, or show him your copy.

programs

After medical evaluation, seek advice from your physician as to your suitability for:

- unrestricted physical activity, probably on a gradually increasing basis.
- restricted or supervised activity to meet your specific needs, at least on an initial basis. Check in your community for special programs or services.

NO to all questions

If you answered PAR-Q accurately, you have reasonable assurance of your present suitability for:

- A GRADUATED EXERCISE PROGRAM - A gradual increase in proper exercise promotes good fitness development while minimizing or eliminating discomfort.
- AN EXERCISE TEST - Simple tests of fitness (such as the Canadian Home Fitness Test) or more complex types may be undertaken if you so desire.

postpone

If you have a temporary minor illness, such as a common cold.

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* Developed by the British Columbia Ministry of Health. Conceptualized and critiqued by the Multidisciplinary Advisory Board on Exercise (MABE). Translation, reproduction and use in its entirety is encouraged. Modifications by written permission only. Not to be used for commercial advertising in order to solicit business from the public.
Reference: PAR-Q Validation Report, British Columbia Ministry of Health, May, 1978.

* Produced by the British Columbia Ministry of Health and the Department of National Health & Welfare.

Health Related Questionnaire (continuation)

After you have read and signed the PAR-Q form, please, read the following and answer either YES or NO:

-Have you ever had back injuries ?

-Have you ever had other bone related injuries (e.g. toes, heels, knees, hips, etc.) ?

-Have you ever had joints, ligaments, tendons injuries or pain related to traumatic states (e.g. operations, irritations, etc.) ?

-Have you ever had any neurological symptoms (e.g. epilepsy, cerebrovascular deficiency, continuous and localized headaches) ?

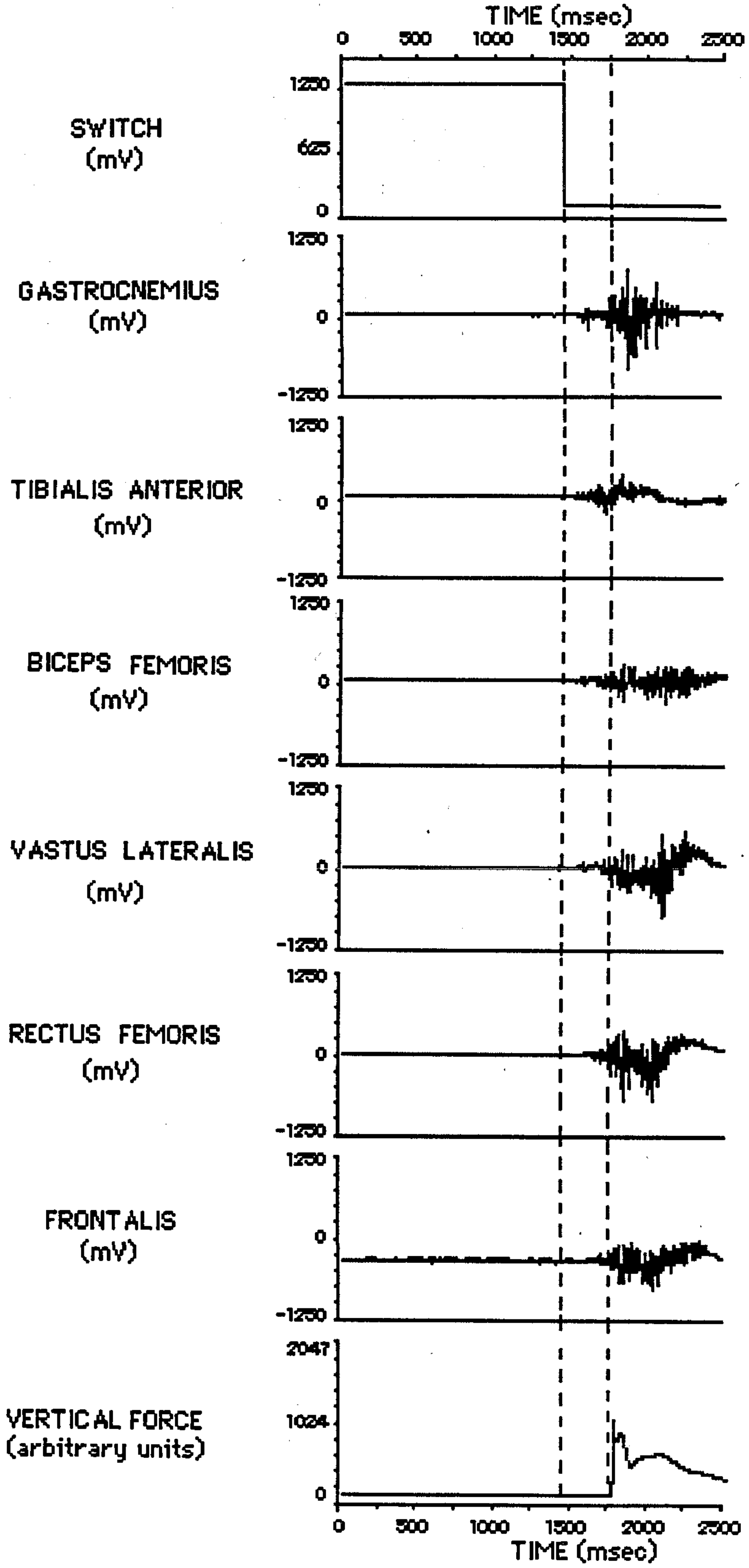
-Have you ever had spinal cord injuries (intervertebral disk compression, disk hernia, localized and sharp pain unrelated to structural problems) ?

DATE:________________________

NAME:________________________

SIGNATURE:___________________

Appendix D Example of raw data plotting for 6 muscle groups, force output, and release time as measured by a drop in voltage as the switch opened.


TIME (msec)
0
500
1000
1500
2000
2500
SWITCH (mV)
1250
625
0
GASTROCNEMIUS (mV)
1250
0
-1250
TIBIALIS ANTERIOR (mV)
1250
0
-1250
BICEPS FEMORIS (mV)
1250
0
-1250
VASTUS LATERALIS (mV)
1250
0
-1250
RECTUS FEMORIS (mV)
1250
0
-1250
FRONTALIS (mV)
1250
0
-1250
VERTICAL FORCE (arbitrary units)
2047
1024
0
0
500
1000
1500
2000
2500
TIME (msec)