Control strategies for landing from a jump-down in boys 7 to 13 years of age: Muscle and kinematic parameters which optimize postlanding stability.

Submitted By:

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A thesis submitted to

the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements for the degree of:
Masters of Science in Rehabilitation Science

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ABSTRACT

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The [illegible] is reserved for the children who voluntarily and patiently participated in this stud

This research was supported by FRSQ.

DEDICATION

I dedicate this thesis with love to my Parents for supporting me in all my dreams ...

And a special dedication for my daughter Jennifer and her laughter.

ABSTRACT

The purpose of the present study was to identify the muscle and kinematic parameters associated with the emergence of a skilled organization of landing from a jump in boys 7 years to 13 years of age. Jumps were videotaped (60Hz) in the right sagittal plane. The digitized coordinates of six landmarks were used to calculate the angular position, velocity, and acceleration parameters for the hip, knee, and ankle joints. Surface EMG signals were recorded for six muscles (Tibialis Anterior, Lateral Gastrocnemius, Soleus, Vastus Lateralis, Rectus Femoris, Biceps Femoris) to obtain the pattern of muscle onsets in anticipation for landing and the modulation of the muscle activity during the impact phase.

Subjects could be classified into three distinct groups based on the pattern of muscle onsets: the Proximal-distal group (PDS), the Transitional group (TS), and the Adult group (AS). The classification reflected a progression from a proximal-distal (PDS) to a distal-proximal (AS) organization of landing. At the muscular level, the progression was associated with: 1) an increased contribution of the ankle to the anticipatory control of landing; and 2) the modulation of muscle activity to reduce the impact ground reaction forces. The strongest kinematic correlates were associated with the increased ability 1) to manage and organize motion-dependent torques; 2) to critically modulate the joint position in anticipation of landing; and 3) to utilize anticipatory muscle activity rather than biomechanical joint limits to manage the impact ground reaction forces.

ABRÉGÉ

L'objectif de l'étude est l'identification de l'organisation des paramètres d'activité musculaire et de contrôle kinématique associés au dévelopement d'une stratégie optimale lors de l'attérissage d'un saut chez les garçons de sept à treize ans. Les mouvements du plan sagittal droit furent enregistrés sur vidéocassette et numérisés à une fréquence de 60Hz. Les coordonnées de six marques anatomiques furent utilisées pour calculer les positions, vélocités et accélérations angulaires de la hanche, du genou et de la cheville. Le signal électromyographique de six muscles de la jambe droite (Jambier Anteriure, Jumeau Latéral, Soléaire, Vaste Externe, Droit Antérieur, Biceps) fut analysé pour obtenir le patron d'activation anticipatoire ainsi que la modulation de l'activité musculaire lors de l'attérissage.

Les sujets sont classifiés en trois groupes selon le patron d'activation anticipatoire: le groupe Proximo-distal (PDS), le groupe Transitionel (TS) et le groupe Adulte (AS). La classification indique une progression du contrôle d'une stratégie proximo-distale à une stratégie disto-proximale lors de l'atterissage. Au niveau musculaire, cette progression est associée aux points suivants: 1) une augmentation de la contribution de la cheville à l'organisation anticipatoire; et 2) une modulation de l'activité musculaire au moment de l'impact pour atténuer les forces réactives. Au niveau de la kinématique du mouvement, la progession est associée à· 1) une habilité d'organiser les forces passives du mouvement; 2) une modulation des positions angulaires en anticipation de l'impact; 3) l'utilisation d'activités musculaires anticipatoires au lieu des limites bioméchaniques articulaires pour contrôler les forces réactives de l'atterissage.

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CHAPTER ONE: INTRODUCTION

1.1 Overview of the Area.

The organization of the motor system is designed to maximize the flexibility of movement strategies, allowing a wide variety of complex movements within the context of a dynamic environment. This flexibility (or variability) is afforded by the principle of motor equivalence whereby the movement profile for an invariant motor end-goal can be subserved by different sets of segmental angles. In turn, these joint angle positions can be controlled by different combinations of muscles and different profiles of activation, force and stiffness (Evarts et al., 1984; Cole and Abbs, 1986; Lacquiniti and Soechting, 1982; Marteniuk, 1990; Pedotti et al., 1978). Variability is therefore considered to be an integral component of the movement organization and is important for avoiding joint limits and eliminating internal singularities during the movement execution (Hollerbach and Atkinson, 1985). The motor system appears to naturally simplify this organizational variability by using consistent and predictable patterns of muscle activation when possible. These simplifying strategies are based on heuristic behaviours which, theoretically, limit the infinite number of degrees of freedom through the control of neuromuscular properties. Furthermore, the predictable and stable motor outcome of these strategies can be easily modified to meet a finite set of environmental constraints (Green, 1969; Turvey, 1977; Nashner and Woollacott, 1979; Nashner et al., 1982; Nashner and McCollum, 1985; Bernstein, 1967; Gibson, 1966; Kugler, Kelso and Turvey, 1980; Kelso, 1982; Gottlieb, 1990).

An effective motor strategy must be adaptive to both internal biomechanical constraints as well as to external constraints imposed by the environment in which the movement is performed. The internal constraints primarily arise from the passive forces at the musculoskeletal level induced by the movement of the linked segments, and include inertial, centripetal, and coriolis forces (Bernstein, 1967; Thelen, 1990, and 1991, Hollerbach and Flash, 1982; Hollerbach and Atkeson, 1987). The primary external constraints to be addressed are gravitational forces, the contact forces with support surfaces, and the available sensory information (Nashner and McCollum, 1985; Stoffregen and Riccio, 1988). The mutuality between the individual's motor strategy and the environment requires that the motor control parameters be specified in real time across an environment-based coordinate system, thereby fulfilling the implicit goal of all movement, "to get to the right place at the right time" (Kelso, 1982) It has been suggested that the control of spatio-temporal errors required to meet this movement goal may be based on a series of sensorimotor transformations, or parallel mappings, of extrinsic cartesian coordinates onto intrinsic body space coordinates. Such parallel mappings would be evolved at the different levels of the movement specification, including muscle, joint, and endpoint levels (Bernstein, 1967; Begati, Gaglio, Morasso, Tagliaso, and Zaccaria, 1980; Soechting and Flanders, 1989a,b).

1.2 Nature and Scope of the Problem.

The development of a movement skill unfolds during the childhood years through trial and error, and involves the gradual modification of a general motor behavior to a more specific motor behavior dictated by the spatio-temporal constraints of the movement goal (Thelen, 1991). The changes in the movement profile during the period of skill acquisition for a specific motor task allows a natural window of observation into the modifications in the motor organization associated with the emerging spatio-temporal accuracy of the motor behaviour.

Traditionally, performance on standardized scales of motor development, such as the Bruininks-Oseretsky Test of Motor Proficiency, are used as an index of a child's motor capacity. However, these tests are based on deterministic scales of success or failure for a specific motor task, and do not address the evolution and quality of the movement pattern as coordination increases (Robertson and Halverson, 1977). Consequently, results from these tests may not be useful in elucidating the organizational principles involved in the acquisition of movement skill. Furthermore, as the motor assessment is based on a deterministic evaluation, clinical intervention also tends toward similar determinism with emphasis being placed on achieving a 'normal motor goal'. Treatment approaches such as the Neurodevelopmental Treatment (NDT) focus on facilitating the child through the motor milestones. However, such approaches fail to address a fundamental pre-requisite for motor control, that is that the state of the sensorimotor system must allow the use of such information in elaborating effective motor strategies Thus, it would be important to first evaluate the range of responses that are available to a child and subsequently to facilitate problem-solving strategies within this particular framework. Problem-solving refers to the strategies that the child may use to reconcile internal and external constraints to produce the sequence of joint and associated muscle torques required to produce an effective evolution of limb positions.

It has been suggested that a predictive model of motor control is implemented gradually, beginning at around six years of age (Zanone et al., 1990), there by paralleling the emergence of sensorimotor abilities between 7 to 10 years of age (Forssberg and Nashner, 1982; Ottenbacher, 1983; Ornitz, 1983; Black et al., 1983; Woollacott, 1987). The implementation of this predictive ability may depend on a sequential, irregular, and perhaps mutually interactive calibration between the visual, vestibular and proprioceptive loops (Assiante et al., 1988; Forssberg and Nashner, 1982). During this implementation period, responses were observed to be slower and more variable. This movement variability may arise from a variety of factors: 1) a frequent shift from one sensory input to another as the child learns to adapt movement strategies to changing contextual conditions (Shumway-Cook and Woollacott, 1986); 2) the child's exploration of available workspace; and 3) the evaluation of the stability of the different strategies at the limits of this workspace (Nashner and McCollum, 1985) The present study addresses the changes in the movement profiles for landing from a jump in boys 7 to 13 years of age, a time period when sensorimotor integration is judged to be functional and the adult pattern of movement is emerging. Recent motor control research supports the idea that coordinated movement patterns reflect the summed sequence of goal directed phases within the movement (Feldman, 1966 and 1980; Robertson and Winter, 1980). The resultant angular motions depend on the net muscle activity across the joints, the mechanical interactions between segments, as well as the external loads applied to the system (Thelen, 1991; Bizzi and Abend, 1983). These are the aspects of motor control that a child is attempting to solve during the childhood years.

To address the emerging capacity of children to manage and organize the passive and active forces into meaningful movement strategies, the task of landing from a jump was selected. The present study focused on the emerging organization of the anticipatory control of landing. Anticipatory activity is initiated during flight in direct relation to the expected amplitude of impact ground reaction forces. Thus, the analysis focused on the organization of the lower limb movement during the flight phase of the jump. During the flight phase, the lower extremity can be modelled as an open kinematic system as there is no contact with external surfaces. Therefore, only inertial and gravitational forces must be addressed in the movement organization As the jump conditions were unchanged across all trials, it is assumed that the kinematic profile during flight is a reflection of the individual's problem-solving strategy. The goal of the problem-solving strategy is to anticipate the impact ground reaction forces and to generate an appropriate configuration of joint and muscle properties to effectively absorb these forces in order to prevent injury and maintain stability. Consequently, the properties of the kinematic profile during flight would reflect the changes in the control parameters associated with the development of motor skill, and may be of value in understanding why some children emerge from this developmental period as skilled individuals while others remain 'clumsy'. The adjective 'clumsy' is often used in reference to children demonstrating soft signs of motor abnormality that are generally attributable to integration difficulties (Johnson et al., 1951). In the present study, it is proposed that variability profiles of joint positions and muscle activation patterns for the lower extremity may serve as sensitive indexes for the evolution of the landing skill. Postlanding kinematic parameters were used to evaluate the success of the different joint organization patterns in managing and adapting to the ground reaction forces.

1.3 Statement of the Problem.

The purpose of the present study was to establish a classification scheme of the modifications in the muscle and joint parameters associated with increasing skill in the performance of landing from a jump in boys 7 to 13 years of age The use of the variability profile for joint position as a basic index of the level of motor performance was investigated (McKinley and Pelland, 1993; Pelland and McKinley, 1991) and its relation to differences in the patterns of muscle activation and joint coordination strategies. The variability profile partitions the flight phase of the jump into distinct epochs defined either by high consistency in joint position across trials or conversely by high variability in joint position. Consequently, skill development is indexed as a change in the modulation profile of the joint position variability.

1.4 Objectives of the Study.

The general objective of this study was to define the parameters of motor performance which are sensitive to developmental effects and thus may be indicative of the problem-solving strategies available during the developmental period of 7 to 13 years of age. for landing from a jump-down This analysis was restricted to the analysis of muscle activation patterns and the corresponding kinematic movement profiles. The kinetic domain of the movement were not addressed in the present study.

The following objectives were addressed in this study:

1) To define the emergent EMG and kinematic strategies involved in controlling landing from a jump in boys 7 to 13 years of age.

2) To classify the control parameters which are associated with the emergence of a skillful landing pattern.

3) To formulate a probable framework of the optimal control parameters during the different stages of skill acquisition.

1.5 Rationale.

The present study attempts to develop a classification of the qualitative changes in the organization of the landing pattern associated with motor development This may provide an insight into the fundamental organizational difficulties which 'clumsy' children may be experiencing. To date, much effort has been concentrated on the description of the motor behaviour of normal and clumsy children with little attempt at merging these observations into a framework of motor control which would include predictive behaviour. Yet, a clumsy behaviour inherently suggests difficulty in predicting the environmental consequences of a given motor strategy Rehabilitation aims at optimizing functional movement strategies to meet the requirements of daily living. This challenge is most evident in the pediatric population in which growth spurts force the child to continually update both internal and external references. Analysis of the structure of the movement profile during these periods of transition may enhance our understanding of the capacity of the motor system to successfully approach novel and unpredictable contexts, as well as revealing problem solving strategies which may limit the emergence of a predictive mode of motor control.

CHAPTER TWO: LITERATURE REVIEW

Three separate research areas are addressed in this literature review. The first section focuses on the control of landing from a jump and includes the following topics: 1) the pattern of muscle activity in anticipation of landing as well as the multi-afferent origin and timing of this feedforward activity; 2) the joint angle configuration and range of motion profiles which function, together with the muscle activation patterns, as a biological damping unit; and 3) the biomechanical significance of these joint and muscle patterns in terms of the joint complex stiffness profiles which optimize the absorption of reactive forces at impact. The second section reviews the joint and muscle organizational principles which have been associated with a skilled execution of the landing task. Finally, the third section addresses the developmental issues associated with motor learning and the transition from a proximal-distal to a distal-proximal control of movement. These topics are discussed in light of the emergence of a predictive model of motor control which generates the smooth velocity profiles characteristic of adult movement. The contribution of feedback and feedforward mechanisms to movement organization and the possible role of the vestibular system as a stable reference for the development of effective sensorimotor strategies are also discussed.

2.1 Anticipatory Muscle Activity for Landing.

Early research on the anticipatory muscular control of landing focused on the electromyographic activity (EMG) evoked during unexpected free-falls in humans

(Melvill-Jones and Watt, 1971). Two bursts of EMG activity were identified during the free-fall. The first burst of activity was timed to the initiation of the free-fall and was identified as a non-specific otolith-mediated startle reflex triggered by the transient linear acceleration at the time of release. The absence of this feedforward reflex activity in self-released falls negates its involvement as an actively planned component of the landing muscle strategy (Vidal et al., 1979). The second burst of activity was specific to the voluntary control of landing and was restricted to the lower extremity muscles directly involved in landing. The timing of the peak amplitude of this second burst of activity was set to time-to-contact, independent of the free-fall height. The timing reference suggests a feedforward organization of the anticipatory activity during the descending phase of flight (Greenwood and Hopkins 1976; Lee and Lishman, 1982; McKinley et al., 1983; Lee and Reddish, 1981; Lacquiniti and Maioli, 1987). Consistent anticipatory muscle activation patterns referenced to the time-to-contact were also reported in humans landing from jumps of various heights (Sidaway, 1989), from forward falls onto the hands (Dietz and Noth, 1981), from a downward step (Craik et al., 1982; Freedman et al., 1976; Melvill-Jones and Watt, 1971a), as well as in monkeys landing from leaps (Dyhre-Poulsen et al., 1980).

2.1.2 Timing of the Anticipatory Activity:

Classically, time-to-contact information is derived from optic flow information which is impinged on the retina as the head moves relative to environmental surfaces during the execution of the task. Optic flow information is therefore congruent with the direction and velocity of the head movement (Gibson, 1966,and 1979; Lee and Aronson, 1974; Lee and Lishman, 1975; Lee, 1980; Koenderink, 1986). However, movement velocity can also be perceived through other proprioceptive signals, including the linear and angular acceleration signals encoded by the vestibular system and the mechanical velocity signal elicited by the stretching forces applied to the musculo-tendinous junction and joint capsule. Through this multi-afferent contribution, the prelanding activity can be organized in the absence of visual cues (Greenwood and Hopkins, 1976; Watts, 1976; Vidal and Lacour, 1979; Dyhre-Poulsen et al., 1980; Craik et al., 1982; McKinley and Smith, 1983).

Independent of its derivation, the accurate estimation of time-to-contact with external surfaces is the critical parameter for the effective organization of the landing strategy. Using a false landing platform, Dyhre-Poulsen and Laursen (1984) were able to 'trick' monkeys such that the onsets of the prelanding activity were timed to the false platform rather than to the actual surface of impact. Similar timing difficulties were reported for humans where visual/vestibular conflict conditions were used to disrupt the accurate estimation of time-to-contact during stair descent (Craik et al., 1982) and with visual perturbations in adults landing from a jump-down (Thompson, 1991). The inaccurate estimation of time-to-contact was associated with a delay in the onset of the prelanding activity coupled with a decrease in the amplitude of the activity. This change in the pattern of activation resulted in a decreased ability to absorb the reactive forces generated at impact. Interestingly, the timing and amplitude modifications of the anticipatory activity were not associated with changes in the temporal organization of the intermuscle activation pattern. Therefore, the effects of the perturbation were restricted to the adaptive timing of the landing strategy to external task constraints while the central construct of the landing strategy was unaffected. However, the central organization of the landing strategy was also found to be a modifiable parameter when the estimation of time-to-contact is disrupted over several trials (McKinley and Smith, 1983). In blindfolded cats, as the non-visual estimate of time-to-contact decayed over the first four trials of a series of jump-downs, a default strategy was adapted which was characterized by a change from a two-burst pattern of anticipatory activity in the elbow extensor to an early continuous activity. This early continuous activity was associated with an increase in body rotation at landing due to the inability of these cats to maintain the projection of the center of mass behind the forelimbs. The authors proposed that the origin of this default anticipatory pattern may lie in the vestibular system, and would be modified to the typical two-burst pattern when accurate visual information is available.

2.2 The Biomechanical Significance of the Anticipatory Activity.

The central goal in the organization of a landing strategy is the optimal absorption of the reactive forces generated at impact to prevent injury and to maintain postlanding stability. A portion of the force transients at impact are naturally absorbed by the inherent properties of structural damping components which include subchondral bone, cartilage, and soft tissue. The remaining forces generated at impact must be absorbed through the biomechanical organization of the lower extremity joints. The primary function of muscles during the landing phase of the jump is the absorption of the mechanical energy generated at impact. The eccentric control of joint motion afforded by the muscles lengthening under tension is the basic kinematic process associated with the attenuation of impact forces (Alexander et al., 1974).

Anticipatory muscle activity sets the muscular tensions required to control the initial postlanding angular velocity of the kinematic links and prevents the collapse of the lower extremity at impact. Eccentric muscle activity experienced at landing brings the body to a halt and optimizes the dissipation of excess mechanical energy as heat. The dissipation of mechanical energy prevents landing forces from inducing oscillations, thereby assuring ground contact (Dyhre-Poulsen and Laursen, 1984). This capacity of muscles to absorb, store, and release the mechanical energy during landing is a function of the controlled stiffness of the involved musculature.

Muscle stiffness is defined as the responding force output of a muscle divided by the distributing change in length during a movement (Loeb, 1985). It is postulated that the muscle stiffness maintains a linear relationship to the movement through intrinsic muscle properties and proprioceptive feedback (Loeb, 1985) and is stabilized through spindle and negative tension feedback from Golgi tendon organs (Houk, 1979). The two basic components contributing to the measurable stiffness developed when a sudden stretching force is applied to an isometrically contracting muscle are short range stiffness (SRS) and slip. SRS is a lightly damped stiffness which is initially used by an actively contracting muscle to resist small, rapid changes in muscle length (Morgan, 1977 and 1978). SRS is primarily contributed by the mechanical application of the lengthening force at the tendon and by the ensuing deformation of cross-bridges at the muscle (Rack and Westbury, 1974; Flitney and Hirst, 1975). Higher levels of isometric tension would yield greater SRS values by increasing the number of attached cross-bridges available to release energy upon deformation (Morgan et al., 1978). As the application of the high velocity lengthening force is maintained, the phenomena of slip would occur. During 'slip', cross-bridges are broken and reformed in a lower number causing a decrease in the measurable stiffness of the muscle. Consequently, the stiffness of a muscle would be less in its response to a lengthening force applied through a large range of motion (Joyce and Rack, 1969). Therefore, biomechanically, the initial sharp rise in vertical ground reaction force experienced at landing could effectively be absorbed by an initial high muscle stiffness. However, as the high velocity of lengthening would persist through the phase of ground contact, muscle tension and stiffness would be lowered due to 'slip'.

The stiffness profile for the ankle joint during landing from a jump was extensively studied by Dyhre-Poulsen (1991). Initial impact forces were found to be controlled by the inherent properties of the muscles, the dynamic stiffness increasing during the initial 10ms of ground impact due to a continuous high isometric prelanding activity in the tibialis anterior (TA) and the soleus (SOL) muscles. The absorption of these impact forces was enhanced by a gradually decreasing muscle stiffness in the contracting ankle musculature which ultimately reached negative values. Negative stiffness implies the loss of mechanical energy, such that little or no storage of elastic energy remains in the muscle and tendon structure at the termination of the landing phase. This energy dissipation assures postlanding stability.

Negative stiffness arises from an interaction between the pattern and level of postlanding activity and the modulation of the H and stretch reflexes prior to landing

During the postlanding phase, the continuous activity in the TA and SOL muscles was transformed to an alternating pattern of low amplitude bursts (40% of Maximum Voluntary Contraction, MVC) and quiescence. This submaximal activation of motor units could produce the lower muscle stiffness required to control the spring-like properties of the muscle while still maintaining a high force output (Joyce et al., 1969). Several mechanisms have been proposed for the generation of this discontinuous post-landing activity: 1) the selective inhibition of alpha motoneurons for brief periods, creating a differential activation of motor units and yielding a segmented EMG with lower amplitudes than elicited by a MVC (Bawa and Tatton, 1979); 2) a selective recruitment of high threshold motor units during the eccentric contractions experienced at landing, maintaining a low activation frequency of the smaller motor units despite the large forces produced (Nardone et al., 1989); and 3) the firing frequency of the alpha motoneuronal pool could be controlled through presynaptic inhibition of the afferents (Capaday and Stein, 1989).

The modulation of the H-reflex patterns were found to contribute significantly to the mechanical damping characteristics of the ankle musculature (Hoffer and Andreassen, 1981; Dyhre-Poulsen and Laursen, 1984). The H-reflex excitability was found to be low during the elicitation of the peaks of the discontinuous postlanding activity. This evidence suggests that the peaks of EMG activity were part of a planned control of landing rather than being reflexively elicited. The strong H-reflex inhibition was initiated more than 100 msec prior to impact, the response progressively decreasing and becoming nearly absent 50 ms postlanding The reflex modulation would preserve the muscle compliance and avoid undesirable oscillations. In fact, this is the central goal of the landing strategy at the muscular level: to preserve the compliance through a low stiffness component of the joints directly involved in absorbing the forces at impact and to reduce postlanding oscillations to a minimum. Negative stiffness would therefore be of decisive functional significance and may be one of the most important muscle properties to be regulated for landing.

2.3 The Ankle as a Biological Damping Unit:

The control of the ankle position at landing is critical for optimizing the neuromuscular features of energy absorption described in the previous section. Two kinematic landing strategies at the ankle were examined in terms of their efficiency in controlling the impact forces: the plantarflexion (PF) strategy and the dorsiflexion (DF) strategy (Gross and Nelson, 1988). In the PF strategy, the initial impact phase is isolated to the metatarsal region of the foot. There is an initial peak vertical impact force associated with metatarsal contact followed by a rounded maximum vertical force which controls the cessation of the downward heel motion. Conversely, in the DF strategy, the initial impact forces are distributed over the metatarsal and heel regions of the foot. This strategy is associated with two peaks of vertical ground reaction force, the first at metatarsal contact, and the second during heel contact. The downward motion of the heel is controlled by a relatively undamped ankle system, the deceleration of the downward motion of the shank being halted by ground contact. The required rigidity of the ankle system in this strategy is enhanced by the anticipatory dorsiflexion which causes a cessation and consequent locking of the ankle joint motion prior to heel contact. Interestingly, the magnitude of the initial impact force was found to be comparable for the two ankle strategies. However, the maximum force experienced was reduced by 22% in the PF strategy where heel contact was prevented. The more controlled lowering of the heel resulted in a decrease in the peak vertical loads which was associated with a single peak acceleration curve with damped vibration. This effectively reduced the number of transients experienced by the lower extremity during the landing phase. Therefore, the ankle serves as an important role in the biological damping system (Gross and Nelson, 1988).

Ankle dynamics form only the first link in distributing the impact forces at landing along the musculoskeletal chain. Recent research has indicated that an optimal distribution of forces in adult humans is achieved when the hip, knee, and ankle joints are flexed prior to landing (McKinley and Pedotti, 1992). Failure to achieve an optimal joint configuration prior to landing disrupts the adequate distribution of impact forces and results in instability. For example, Cavanagh (1970) observed that a sustained contraction of the triceps surae muscles concomitant with knee extension at landing induced an oscillatory motion which decreased in amplitude exponentially with time, as in a damped harmonic motion (Cavanagh, 1970 and 1971). The force-length curve of the elastic structures producing this oscillatory motion were found to be similar to that of the series elastic elements in the isolated muscle. This would suggest that the postlanding oscillations were passively induced by excess energy stored within the muscle rather than through an active control of the muscle properties. Again, this underlines the importance of the negative stiffness parameter at landing to assure post-landing stability.

2.4 Definition of a Skilled Landing Strategy:

The primary descriptor of a 'skilled' landing is the optimal absorption of forces at impact which reduces the impact transients to a minimum and maximize stability. The adaptive strategies for a skilled landing performance have recently been investigated in adults by McKinley and Pedotti (1992). Results indicated that the absolute ankle position at landing was critical in the skilled landing pattern, the performance index rapidly degrading when wrong ankle positions were chosen for a particular surface compliance In fact, skilled individuals adapted to differing landing surface compliances primarily through adjustments at the ankle joint. In contrast, the adaptive strategies for the unskilled individuals were characterized by a non-specific 'default' strategy with adjustments occurring both at the ankle and knee joints.

2.5 Developmental Issues:

2.5.1 Motor Learning:

The acquisition or learning of a motor skill gradually unfolds on a time scale through the childhood years. During this time, general motor behaviors are gradually modified and adapted to yield stable and consistent movement patterns typical of normal adult behaviour (Kelso, 1982). Motor skill implies a spatio-temporal precision, with the ideal complement of actively-produced and passively-induced movements operating under a wide variety of conditions (Berstein, 1967; Connolly, 1977; Turvey, 1977; Kelso, 1982).

In learning a motor task, children initially experience difficulty in both the appropriate sequencing of participating limb segments as well as in the regulation of the required muscle forces. Developmental studies have indicated that the initial formation of a movement pattern is characterized by a proximal-to-distal control of muscles and kinematic links (Horak and Nashner, 1986). This proximal-distal control is usually coupled with a coactivation of joint antagonists (Thelen, 1991). This antagonist coactivation is effective in reducing the velocity of the kinematic links as well as excess motion-dependent torques. This preliminary movement strategy is useful in providing the stability which is a prerequisite for purposeful movement patterns (Thelen, 1991). It is important to note that the controlled velocity afforded coactivation is also transiently observed in adult motor behaviour either when faced with unfamiliar motor tasks as well as in the generation of rapid movements (Hasan, 1990). The presence of coactivation in the lower extremity during stance and gait perturbation may be normal in small children, but is a sign of motor system impairment when present in older children (Marteniuk, 1990).

Biomechanically, antagonist coactivation reduces the velocity of the kinematic links. This resultant slowing (or stiffening) of the limb may be used to interrupt the natural oscillatory dynamics of the system during movement. For example, Thelen (1991) observed that coactivation allowed infants to convert nonspecific flapping movements of the arm into a functional reaching movement toward a toy. The modulation of limb stiffness through coactivation represents the first strategy to be recruited for the voluntary control of movement, combining a slow velocity and low compliance of the limb to provide steadiness and accuracy. Although it is an effective movement strategy during early learning periods, coactivation produces high joint loads which predisposes the joints to injury and thus may be undesirable as the child grows. As the need for coactivation during movement decreases, more distinct muscle activity patterns appear (Moore and Marteniuk, 1986). These more elaborate activity patterns usually include the inhibition of ongoing muscular activity known as pre-motor silence or PMS (Takanashi and Yoshiaki, 1980). In fact, the reciprocal activation of antagonist muscles characteristic of adult movement patterns emerges in conjunction with the development of PMS (Gatev, 1972). Therefore, PMS is considered to be an important feature of developing coordination strategies in early childhood.

Functionally, PMS facilitates the initial acceleration of the kinematic segment with the duration of the silent period being directly related to the magnitude of the acceleration (Walter, 1984; Hallett and Marsden, 1979). It has been suggested that PMS arises from inhibitory mechanisms at the spinal and supraspinal levels (Conrad et al., 1983). However, this mechanism is unlikely since the alpha motoneuronal refractory periods are less than the shortest PMS duration (20 ms). A more functionally based neurophysiological view suggested that PMS could evolve directly from the muscle mechanics (Walter, 1984). The assumption is that the joint is initially in a state of equilibrium. The onset of PMS causes a disequilibrium which yields a brief initial movement reversal referred to as the stretch-shortening cycle (Norman and Komi, 1979; Wilson et al., 1991). This initial movement reversal applies a lengthening force to the agonist muscle which increases the force generated on the subsequent concentric burst of activity due to the length-tension properties of the muscle (Rack and Westbury, 1969). This increased agonist force output would in turn produce a greater torque at the joint and a greater initial acceleration of the limb segment in the direction of the planned movement. The relationship between PMS duration and peak acceleration is thus accounted for by the stretch-shortening cycle, longer periods of inhibition resulting in a greater degree of agonist lengthening and moment. PMS may be influenced by learning, the frequency and discrete timing of the PMS having been shown to increase with practice (Walter, 1984) and training (Dyhre-Poulsen, 1984, 1991).

2.5.2 Feedback and Feedforward Processes.

Through the developmental years, the control of a movement is progressively altered through trial and error, the pattern gradually exhibiting the smoothness and consistency which is characteristic of adult movement profiles (Cooke and Brown, 1990). This movement stability relies on feedback and feedforward processes. Feedback and feedforward control systems develop in parallel, using trial and error and the knowledge of past events and contingencies to learn, adapt, and achieve their effectiveness (Haas and Diener, 1988). The repeated multimodal correlation of an exploratory movement with the sensory changes that it engenders would therefore be a primary factor for the development of stable and functional movement strategies (Wollacott et al., 1987; Thelen 1991; Bernstein, 1967). In this scheme, a movement plan would be based on sensory consequences and the movement patterns generating the desired feedback information would be gradually imposed upon the natural or intrinsic dynamics of the body during learning (Thelen, 1991). In support of this view, Woollacott et al. (1987) found that postural responses in children were not functional prior to the experience of stabilizing the center of mass. Through this correlative learning process, the most stable and efficient movement pattern for a task is selected from all the existing possibilities (Bernstein, 1967; Kugler and Turvey, 1987).

Present views on motor development support the principle that control is first established through feedback and later through feedforward control (Haas and Diener, 1988). Studies examining the changes in the movement profile during visual pursuit tasks have revealed that during development, there occurs a decrease in the use of visual feedback mechanisms, the corrective saccades decreasing with the acquisition of smooth feedforward modulation. It is postulated that this feedforward modulation allows a predictive model of outcome to be established and eliminates the discontinuities in the movement velocity profile introduced by feedback mediated corrections (Zanone et al., 1990). In the predictive model of motor behaviour, a movement is initially evolved from a general motor plan which is progressively updated through feedforward and feedback mechanisms during the task execution to calculate the behaviour required to meet the dynamic goal. The pattern of this anticipatory motor behavior becomes more accurate and stable with age. This spatio-temporal stability may be related to the maturation of both sensory and motor systems such that various sensory inputs can be evaluated, integrated, and coordinated with motor information to allow a smooth interaction of feedback and feedforward behavior (Zanone 1990; Day and Marsden, 1982).

2.5.3 Sensory Integration.

The predictive model of behaviour proposes that to generate the smooth velocity profiles characteristic of adult movements, the motor system must have access to both accurate predictive feedforward and correcting feedback processes. It has been proposed that the stability of these processes is constrained by the developmental state of the vestibular system.(Ottenbacher, 1983) The vestibular system is thought to be critical for the integration of sensorimotor information . In this capacity, the vestibular system would function as a stable orientation reference or estimate of behavior to which afferent information may be evaluated for context-relevancy (MacKay, 1980; Shumway-Cook and Woollacott, 1986; Black et al., 1983; Horak et al., 1988; Nashner et al., 1982).

Central vestibular function is modified throughout childhood and gradually reaches adult values around 9 years of age (Ottenbacher, 1983; Ornitz ,1983). These developmental changes are characterized by an increase in the time constant of the vestibulo-ocular reflex (VOR) and a concomitant decrease in its gain. The time constant changes reflect the increased modulatory effect of central structures (such as the brainstem reticular formation) on the activity of the vestibular nucleus. The modifications in the gain of the VOR reflect direct modulatory changes in the vestibular nucleus itself. The putative site for the required integration of visual, vestibular, and proprioceptive information signals is the lateral vestibular nucleus, the resultant input being transmitted to the motor system through the lateral vestibular spinal tract (Waespe and Henn, 1978; Wilson and Melvill-Jones, 1979).

Prior to this development, children would present difficulty in the formation of a context-relevant frame of reference. In support of this view, Forssberg and Nashner (1982) noted that children 7 to 8 years of age were unable to maintain postural stability under conditions of conflicting orientation information. These children were relying on context-inaccurate visual cues and their performance was comparable to that of vestibular-deficient patients (Black et al., 1983). Thus, prior to the full development of vestibular function, children may predominantly rely on one orientation signal rather than on an interactive 'set' of orientation information. In fact, toddlers were observed to dominantly rely on visual information for postural control, even when visual cues were inappropriate (Butterworth and Hick, 1977; Lee and Lishman, 1982) Consequently, when presented with destabilizing visual information, postural instability persisted and toddlers continued to fall with little or no habituation over repeated trials. This visual dominance inhibited the capacity of the postural system to accurately detect external sensory conflict information. As a result, the postural system was unable to generate an adaptive movement behaviour to meet the sensory conditions of the task

2.6 Summary.

In summary, the gradual emergence of stable and predictable movement patterns during the childhood years can be clearly associated with the development of the individual's integrative capacity. This integration must occur at distinct levels of the motor organization, from the musculoskeletal and neuromuscular levels at the periphery to the central mechanisms which generate and coordinate movement. The end result of this internal sensorimotor capacity must also be integrated with the dynamics of the environment in which the motor behavior is performed. Learning and practice are essential at this level to correlate the behaviour with its sensory consequences.

CHAPTER THREE: METHOD AND PROCEDURES

3.1 Experimental Methodology.

Subject Population: The subject group consisted of nine boys ranging in age from 7 years (±6mths) to 13 years (±6 mths). The subjects were screened according to the following exclusion criteria: no medical history of developmental or neurological abnormalities, no neuromuscular or orthopaedic dysfunction, and no known visual-vestibular disorders. Subjects were within the 80th percentile for anthropometric parameters of height and weight for their respective age group (from Deanne and Wilson, 1988).

Assessment of Motor Development: The subjects' motor developmental age was assessed using the Short-Form Bruininks-Oseretsky Test of Motor Proficiency This sensory-motor evaluation is valid for the assessment of motor performance in children ages 4 years 6 months to 14 years 6 months. Fourteen items are scored to determine the child's strength, speed, and dexterity abilities, with a single composite score providing the estimate of general motor proficiency from which the developmental age is approximated (Bruininks, 1978). The strength of this motor evaluation is that it has good reliability in the 6 to 13 year age bracket for most subtests, and may be administered in 15 to 20 minutes. However, the assessment fails to evaluate the quality of the movement and the fine motor skill items have low content validity. The age and motor developmental scores for all individuals are reported in Table (1).

TABLE 1

MOTOR DEVELOPMENTAL INDEX

Subjects	Age yrs (mo)	Motor Scores (B/O)
VC	12 (10)	66%
LF	7 (2)	99%
JV	7 (1)	99%
MPC	6 (8)	99%
DPC	6 (8)	99%
FS	7 (5)	72%
JND	7 (4)	88%
FB	8 (6)	79%
MR	10 (1)	31%

Legend:

Subjects: Identification of the nine individuals
Age: Chronological Age
Motor Developmental Scores: Percentile ranking on the Bruininks-Oseretsky Test of Motor Proficiency

3.2 Experimental Protocol.

The jump-downs were performed from an adjustable 40 X 60 cm rigid platform, secured to a metal frame bolted to the floor and grounded. The position of the platform was controlled by a hydraulic system, eliminating both mechanical and electrical noise The height of the platform was adjusted to the height of the lateral tibial plateau for each individual, thereby standardizing the height of the jump with respect to individual anthropometric profiles. Subjects were required to perform knee height jump-downs, leading with the left foot and landing with both feet simultaneously onto a rigid surface This modified jump-down was selected based on results of a pilot study which revealed that the younger children were more consistent in performing this modified take-off strategy with a lead leg rather than a propulsive phase requiring a coordinated movement of both lower extremities (Pelland and McKinley, 1991). The subjects' hands were held lightly to standardize the contribution of the upper extremities to the movement, as well as providing security against falls.

3.3 Jump Protocol.

A practice session allowed the individuals to become familiar with the execution of the landing task. During the experimental session, subjects were required to execute a series of ten (10) trials under each of three visual conditions. normal vision (NV), occluded vision (OV), and stabilized vision (SV). The present thesis addresses the results for the normal vision condition A brief description of the three visual conditions is provided: 1) For the Normal Vision condition, a collar prevented the direct viewing of the landing surface thereby eliminating differences across the three visual conditions related to the perception of time-to-contact information; 2) For Occluded Vision, swimming goggles filled with foam were worn to eliminate visual cues; and 3) For Stabilized Vision, a visual conflict dome adapted from Shumway-Cook and Horak (1986) provided a constant visual field. For all three visual conditions, visual information update prior to task execution was permitted as often as comfortably required by each individual. Blocked rather than random trials were selected as the control requirements, for blocked trials conformed more closely with the objectives of the study: to define the emergence of stable motor control landing strategies. Blocked trials involve a repetition of similar neuromotor synergies and cognitive processes on repeated trials, while random trials require a different action plan and motor response on succeeding trials (Lee and Magill, 1983).

3.4 Data Acquisition:

Electromyographic Data (EMG): Raw EMG signals were obtained using bipolar disposable skin electrodes (Medi-Trace, silver/silver-chloride). The skin overlying the motor point of each muscle was prepared and the electrodes placed at a 2 cm bipolar distance. The EMG was recorded from six right lower extremity muscles: tibialis anterior (TA), lateral gastrocnemius (LG), soleus (SOL), vastus lateralis (VL), rectus femoris (RF), and biceps femoris (BF). A ground electrode was placed over the head of the fibula.

EMG Recording: The signal was differentially amplified (x10) at the pre-amplifier, and subsequently bandpass filtered 10-500 Hz and amplified (x100). The signal from the amplifier was stored on Beta video tape (Sony Super Beta System) using a Vetter Pulse Code Modulator (PCM-Model 4000; 16 bit resolution). The EMG signals were monitored online on an oscilloscope (Hitachi, Model V-134) during the experimental session. The signal was then acquired offline (AT computer. Everex 160) for analog to digital conversion (A/D) using Computerscope Software (ISC-16; RC Electronics). A 1KHz sampling rate was used for the A/D conversion over a ±5 volts dynamic range.

EMG Analysis: The digital EMG signal was analyzed using ANAPAC Signal Analysis Software (Run Technologies). The EMG signal was fullwave rectified and the DC offset was adjusted for individual muscle channels. A resting baseline activity was established for individual muscles by averaging the activity for a 10 ms period during quiet standing prior to movement initiation. The onset of significant EMG activity was operationally defined as a rise above the 95% confidence interval of resting baseline activity for a minimum duration of 10 ms. Cross-correlations (r=0.75) of the EMG signals in the time and amplitude domains were used to identify trials in which signal artifact was introduced during the high impact transients at landing. Trials with correlation values above the r=.75 limit were removed from further EMG analysis. The EMG signal was then low-pass filtered at 10Hz (symmetric, non-recursive finite impulse response digital filter with Lanczos' smoothing function; 101 length) was efficient in eliminating movement artifact during flight without altering the signal frequency of amplitude.

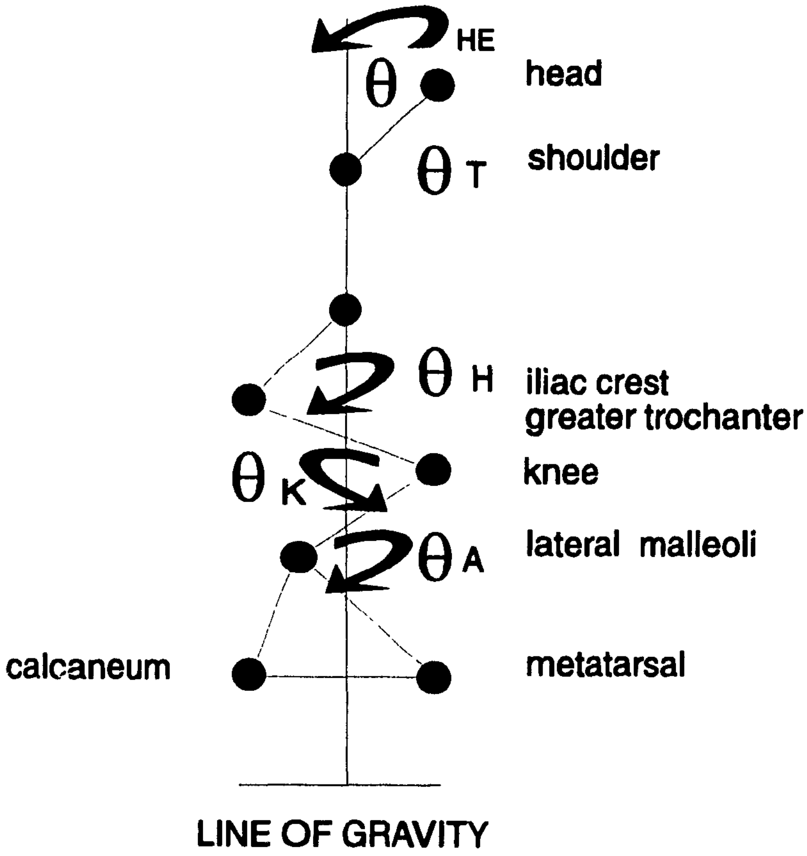
Temporal Events: The critical temporal events of the jump-down correspond to the takeoff and touchdown. These critical events were recorded using pressure-sensitive footswitches secured to the subjects' shoes at the base of the great toe, the ball of the foot, and at the heel. The footswitch signal was low-pass filtered and stored simultaneously with the EMG and kinematic signals allowing the coupling of the EMG and kinematic data.

Kinematic Data: Subjects were dressed in black tights and T-shirt. Reflective markers were secured to the lateral border of acromion (shoulder marker), to the anterior superior iliac crest (center of gravity marker), to the greater trochanter (hip marker), to the lateral knee joint line (knee marker), to the lateral malleolus, heel, base of the fifth metatarsal (ankle marker), and to the top of the helmet (head marker). The body was therefore modelled as a six-linked segment body with the following angles obtained for analysis: the head, the trunk, the hip, the knee, and the ankle angles (see Figure 1).

Kinematic Recording: The jump-downs were video-taped in the right sagittal plane (lag leg) with a Panasonic Digital WV-D5000 strobe camera at a 60Hz sampling frequency. This sampling frequency is adequate for the analysis of human movement (Cheetam and Scheirman, 1988). However, this sampling rate may not be sufficient to capture the high velocity landing phase. To address this sampling limitation, the recording camera was equipped with a strobe shutter system utilizing a 1 ms shutter speed to capture the marker image. This system yielded the greater resolution required during landing. A second

Figure 1. Positions of the landmarks defining the six-linked segment model. The figure defines the segments forming the angles used in the kinematic analysis: Ankle, Knee and Hip angles which are addressed in the present study, as well as the trunk and head angles.

METHODS FOR DATA COLLECTION



EMG COLLECTED FROM :

TA = TIBIALIS ANTERIOR

LG = LATERAL GASTROCNEMIUS

SOL = SOLEUS

VL = VASTUS LATERALIS

RF = RECTUS FEMORUS

BF = BICEPS FEMORUS

ANGLES MEASURED :

HE : HEAD = HEAD / SKOULDER / VERTICAL

T : TRUNK = SHOULDER / ILIAC / VERTICAL

H : HIP = ILIAC / TRONCHATER / KNEE

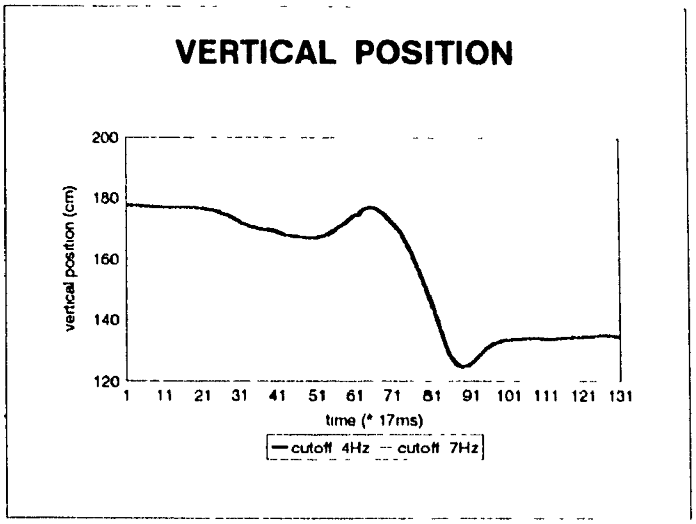
K : KNEE = TRONCHATER / KNEE / MALLEOLI

A : ANKLE = KNEE / MALLEOLI / METATARSAL camera (Panasonic WV-3170) recorded the footswitch signal displayed on a storage oscilloscope (Hitachi, Model V-134). A system switcher (Panasonic WJ-3500) was used to synchronize and merge the kinematic and footswitch signals. The combined signal was stored on VHS tape.

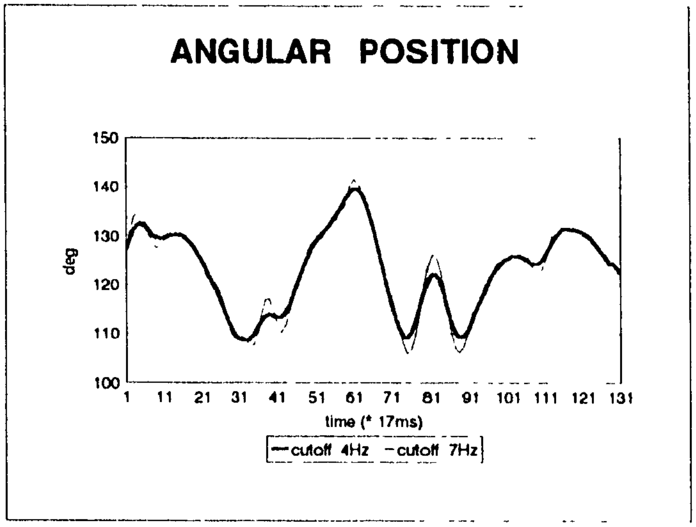
Kinematic Analysis: The kinematic data was analyzed off-line on an AT computer (Everex, 160) with Peak Performance Motion Measurement Systems (Peak Technologies). The data was filtered using a third order non-recursive Butterworth filter. A 4Hz cutoff frequency was selected to filter the raw signal rather than the 7Hz frequency suggested by Winter (1979) for the analysis of human movement. In this study, the 7Hz cutoff frequency was associated with increased oscillations in the signal trace, particularly for the angular velocity component. Figure (2) illustrates sample traces for the vertical linear position component, angular position, and angular velocity signals at the knee joint. Comparison of the two signal traces revealed the following: 1) there was no phase-shift between the two frequencies; 2) the 4 Hz cutoff frequency was associated with a damping of the amplitude profile of the signal, particularly for angular velocity; and 3) the 7 Hz cutoff frequency was associated with oscillations of the signal, particularly for angular velocity. As the aim of this study was to identify the stable organizations of the landing pattern without addressing the kinetics of the movement, it was felt that a smooth signal was of greater value despite the smoothing of the peak amplitude information. The decreased length and mass of the limb segments in children are possibly the main contributors to the increased oscillations at the 7 Hz, a small

Figure 2. Contrast of the 4 Hz and 7 Hz cutoff frequency for the low pass filtering of the kinematic signal for the vertical position, the angular position, and the angular velocity parameters. The 4 Hz frequency (which is used in this study) is represented with the 'thick' trace and the 7 Hz frequency with the 'thin' trace. The X-axis corresponds to the time, each value representing 17 ms (the sampling frequency of the kinematic data).

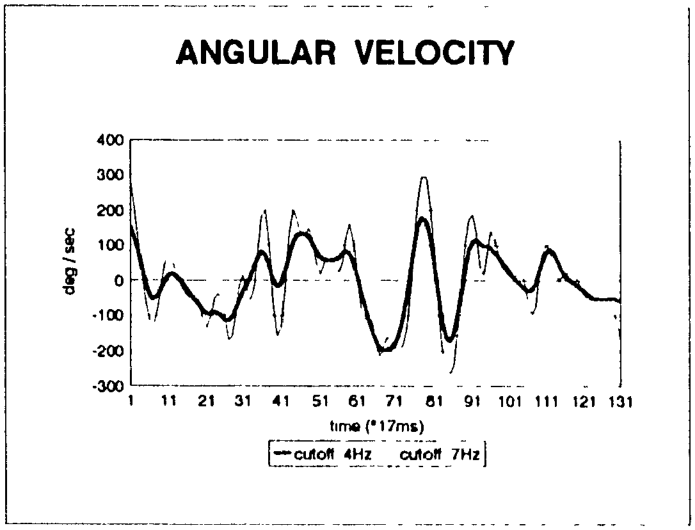
FILTER 4Hz vs 7HZ



VERTICAL POSITION



ANGULAR POSITION



ANGULAR VELOCITY

change in the dynamics resulting in larger oscillatory motion at the limb endpoint as compared to adults.

3.5 Data Normalization:

For intertrial comparisons within and across subjects, the kinematic data was normalized to flight time duration using the following 'rubberbanding' formula (adapted from Winter: B. McFayden, personal communication).

ND(i) = OD (IVAL) +((OD)(IVAL + 1) - (OD(IVAL)) *FVAL

(where ND = new data; OD = old data; IVAL = interval between data points; FVAL = time interval for normalization (number of points in file / number of points to normalize over).

With this 'rubberbanding' normalization technique, the endpoints of the data string (the take-off and touch-down points) are fixed and the intermediary data string is either lengthened or shortened to a standardized length. The shape of the function is preserved because the normalization procedure adjusts only for differences in the length of the flight time duration to allow a statistical analysis across trials and subjects. The Nyquist theorem was observed in determining the length of the normalized data string.

3.6 Statistical Analysis.

The statistical measures in this study were used as tools to describe the emergent movement organization rather than to determine inferential relationships. For the EMG data, statistical analysis was applied only to the onset of EMG activity. Intersubject comparisons of the range of onsets were based on 95% Confidence Intervals since confidence intervals provide an indicator of the range within which population means are expected to occur (Dunn and Clark, 1974). The other parameters of the EMG patterns, including the duration, amplitude and frequency values, are related to the kinetics of the movement and will be addressed in further research. Independent t-test analysis was used for the intersubject comparison of discrete kinematic values: central joint tendency position and range of motion. A descriptive analysis, correlating kinematic with muscle activation profiles, was the main analytic tool used in this study.

3.7 The Variability Profile.

The variability profile is a stochastic analysis addressing the intertrial variation in joint position during the flight phase of the jump-down. To obtain the variability profile, the joint position coordinates across all trials for each individual were normalized to the standard flight time duration using the rubberbanding technique A mean joint position and corresponding 95% confidence interval was then calculated for each 1ms time interval across the normalized flight time. A representative profile is illustrated in Figure (3). The profile of position modulation was defined by two critical levels of intertrial variability which corresponded to a variability minimum and a variability maximum: 1) The minimum level corresponded to time regions during which the variability in joint angle position decreased to below 30% of the maximum within-subject variability intervals. These time regions represent epochs of flight during which a strict control of joint position was achieved and are represented within the 'hatched' regions of the graph; and 2) The maximum level corresponded to time regions during which the variability in joint angle position increased to above 70% of the maximum within-subject variability interval. These time regions represent epochs of flight during which a loose control of joint position is required and are represented within the 'solid' lines on the graph.

Figure 3. The Variability Profile for the intra-subject analysis of joint position across the 10 trials. The graph indicates the 95% Confidence Interval range for each 1% interval across the normalized flight duration (0% corresponds to takeoff and 100% to touchdown). Solid vertical lines and 'filled' interval values indicate the critical joint positioning regions: minimum variability intervals (< 30% maximum vairiability) is illustrated within the 'hatched' regions of the graph while maximum variabilty intervals (>70% maximum interval) is illustrated within the 'open' regions The joint angle positions are plotted along the Y-axis.

VARIABILITY PROFILE ANALYSIS

ADULT KNEE

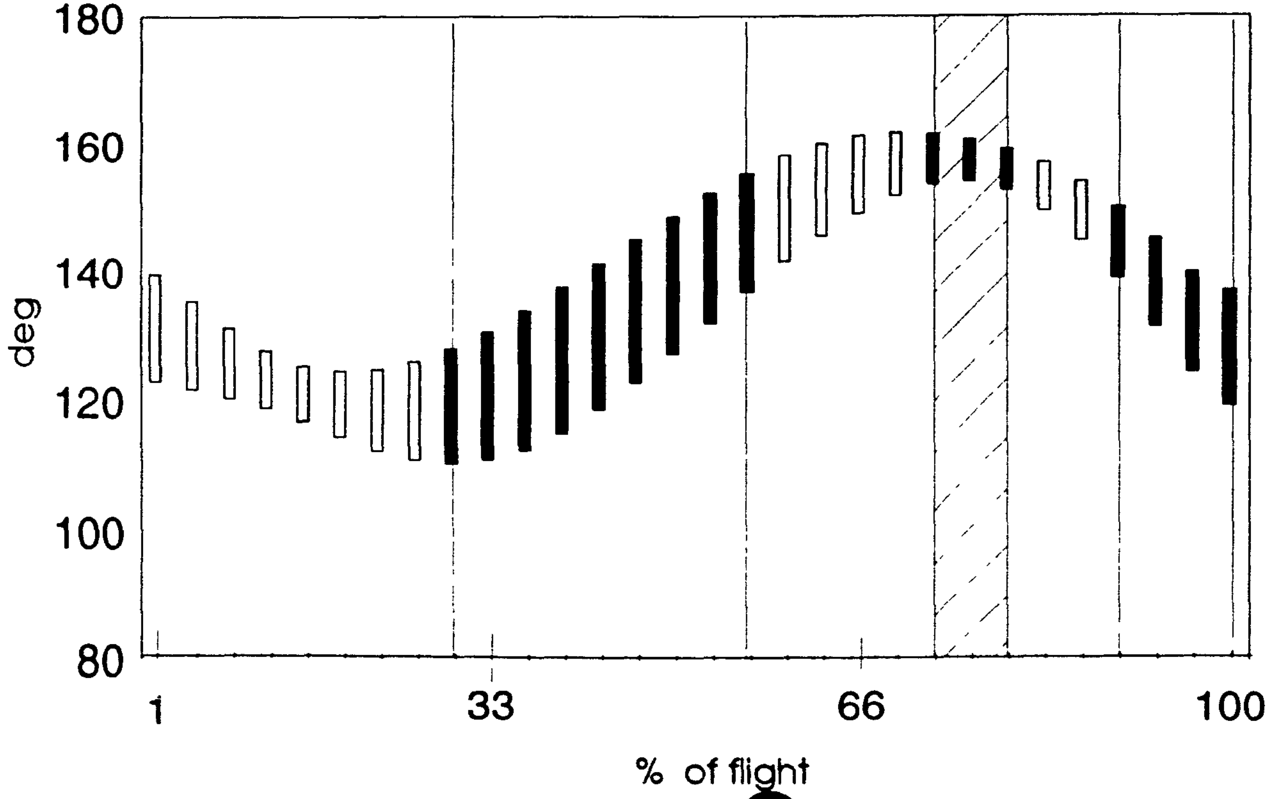
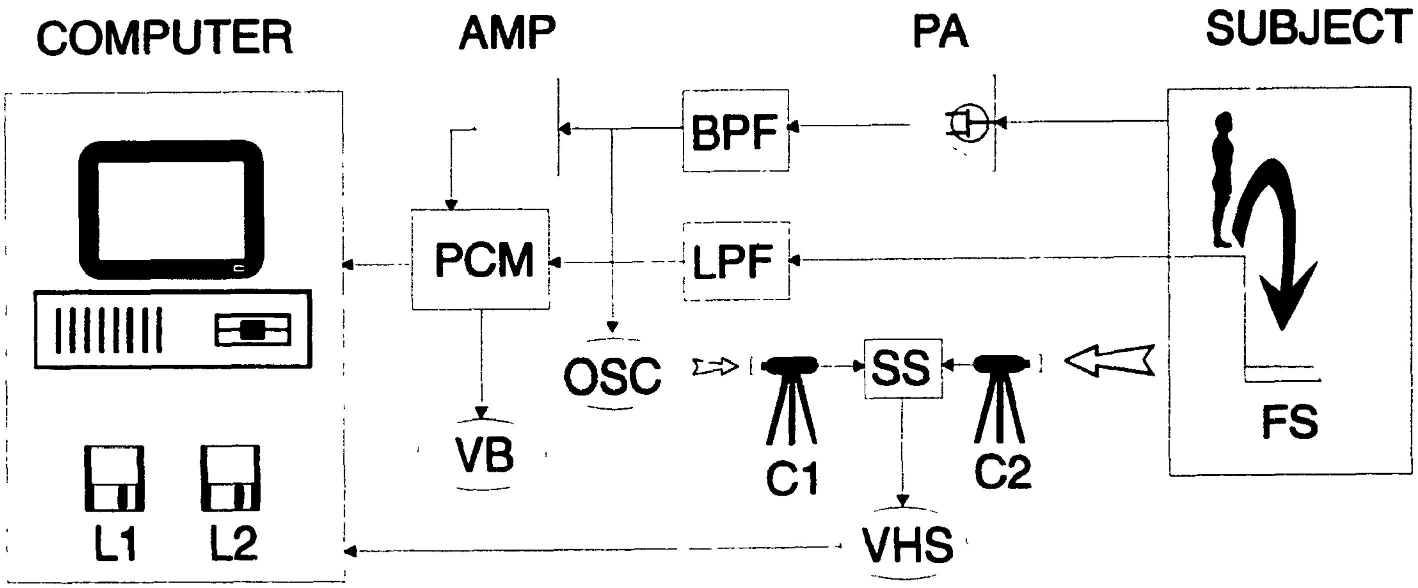


Figure 4. Flow diagram of the equipment set-up utilized for the data acquisition

EQUIPMENT SET-UP FOR DATA ACQUISITION



EMG

PA : PRE-AMPLIFIER X 10
BFP : BANDPASS FILTER ; f1 = 10 HZ f2 = 500 HZ
AMP : AMPLIFIER X 100
OSC : STORAGE OSCILLOSCOPE
PCM : PULSE CODE MODULATOR
VB : VIDEO BETA TAPE
L1 : ANAPAC ANAYSIS

KINEMATIC

C1 : STROBE CAMERA
C2 : CAMERA #2
SS : SYSTEM SWITCHER
VHS : VHS VIDEO TAPE
FS : FOOTSWITCH
LPF : LOW PASS FILTER ; f1 = 10 HZ
L1 : PEAK PERFORMANCE

CHAPTER FOUR: RESULTS

4.1 INTRODUCTION.

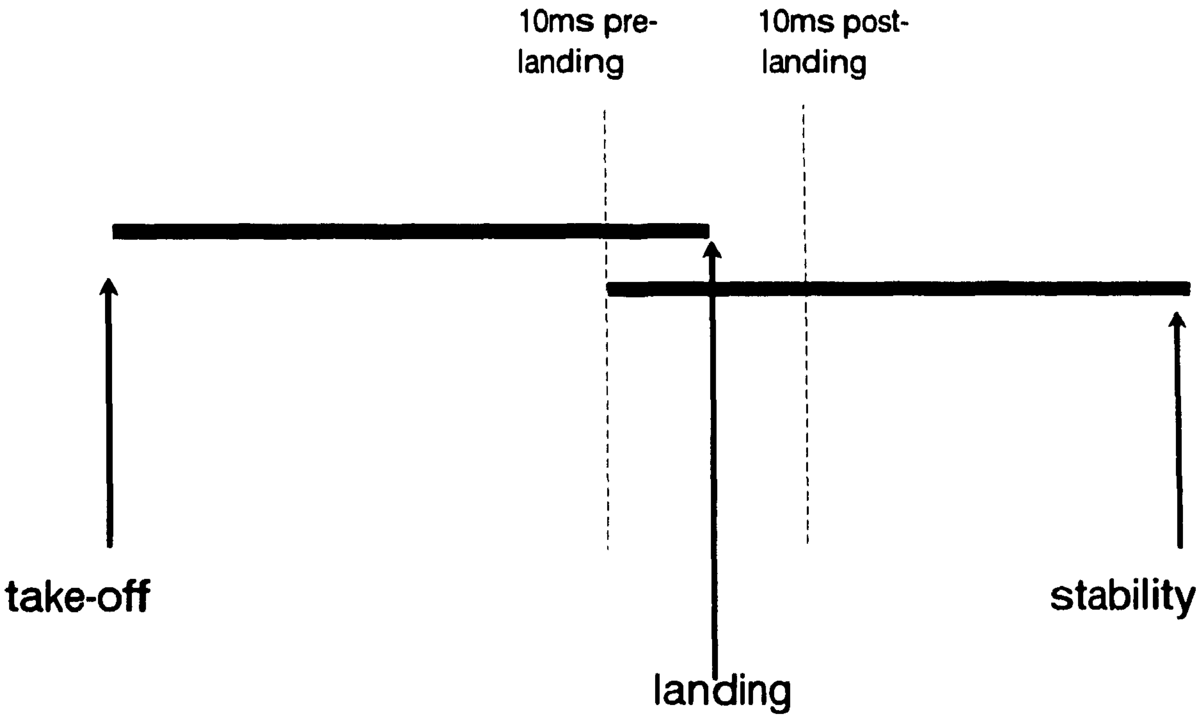
The focus of this study was to identify differences in the organization of the lower extremity muscle and kinematic parameters controlling landing from a jump in boys 7 to 13 years of age. A distinct progression from a proximal-distal to a distal-proximal muscle activation pattern related to landing was identified The emergence of the distal-proximal activation pattern was associated with an increased ability to modulate the angular position and muscle activity parameters during the final phase of flight The increased modulation of control parameters during the final phase of flight was associated with a more efficient anticipatory control of the impact ground reaction forces Increased efficiency of anticipatory control of landing is reflected as a decrease in the accelerative forces experienced at the center of gravity during the impact phase and consequently to an increase in postlanding stability

4.2 Muscle Onset Patterns for Landing.

The pattern of muscle onsets associated with landing specifically refers to EMG activity found within the following limits. a) the activity is initiated between take-off and the first 10 ms postlanding; and b) the activity is terminated either postlanding or in the last 10 ms prior to landing (see Figure 5) The pattern of muscle activation for landing was defined by the mean onset of activity (referenced to landing) and the corresponding 95% confidence intervals of all the trials for each individual Three distinct muscle

Figure 5. This graph indicates the time limits for the definition of Landing Muscle Activity. Landing is indicated with a 'solid' vertical line and the time limits with 'dotted' vertical lines. Landing Muscle Activity is delimited as follows: onsets are initiated between take-off and the first 10 ms postlanding, with offsets within 10 ms of landing (prelanding phase to the left of landing) or in the postlanding phase (to the right of landing).

Definition of Landing Muscle Activity



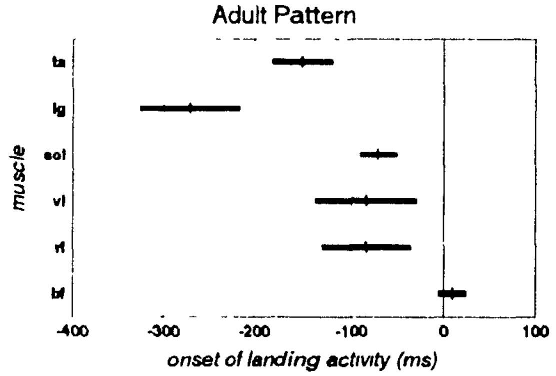
activation patterns were identified: the **Adult Pattern (AS)**, the **Transitional Pattern (TS)**, and the **Proximal-distal Pattern (PDS)**. The three muscle activation patterns are illustrated in Figure (6); landing corresponds to T_0 on the abscissa, with pre-landing activity onsets designated by negative time values and postlanding activity onsets by positive time values.

Variability in the Onsets of Muscle Activity: The 95% confidence interval limits for the three muscle activation patterns indicate a high variability in the onsets of the muscle activity for landing across individuals. As the subjects displayed a wide range of flight durations, this variability in onset values was explored as a function of the variability in flight duration. The correlation values between the onset of muscle activity for landing and the flight time duration are reported in Table (2) for all individuals A significant correlation between these two parameters was found only for one muscle, the VL, in one individual, VC of the Adult Pattern group. The lack of significant correlations between the timing of the landing muscle activity and the flight time duration would support the view that the onset variability is an inherent component of the landing strategy.

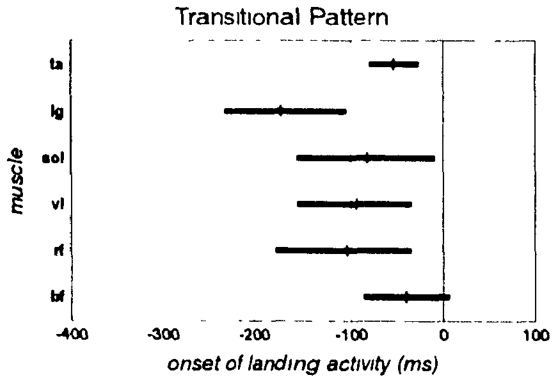
Definition of the Muscle Onset Patterns: The term **Adult Pattern** underlines the similarity of this pattern with the distal-to-proximal sequence of muscle activation reported for adult subjects landing from a jump (Thompson, MSc Thesis, 1991; McKinley and Pedotti, 1992) The AS pattern was initiated distally with activity in the plantarflexor muscle Lateral Gastrocnemius (LG), followed by activity in the dorsiflexor

Figure 6. Muscle Onset Patterns for 3 individuals that adopted either: A) the Adult, B) the Transitional, or C) the Proximal-to-distal pattern. Each graph represents the 95% Confidence Intervals (horizontal bars) and mean (vertical tick marks) onset of the six muscles for the 10 trials of one representative individual.

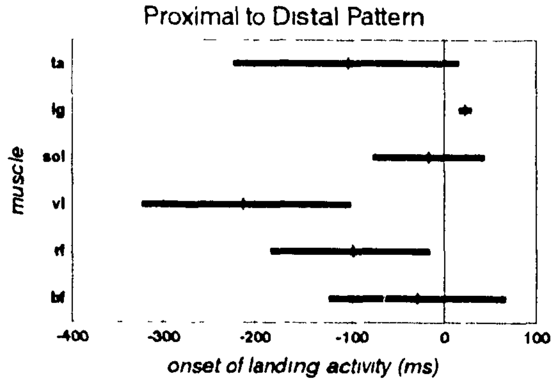
Muscle Onset Patterns



(vc)



(lf)



(dpc)

TABLE 2

CORRELATION BETWEEN FLIGHT TIME DURATION AND ONSET OF LANDING ACTIVITY

	VC	LF	JV	MPC	DPC	FS	JND	FB	MR
TA	-.19	.16	.39	-.30	-.56	-.06	.53	-.11	-.10
LG	-.36	-.12	-.17	.56	.66	0	-.63	-.25	--.42
SOL	-.70	.48	.21	0	-.30	-.18	.19	.07	.38
VL	*.81	-.23	-.10	0	.36	.47	-.56	.08	-.07
RF	.58	.23	-.30	-.36	-.67	.61	.61	-.23	.03
BF	-.17	-.35	-.01	-.70	-.02	-.10	,28	-.05	.68

Legend: **Subjects:** represented horizontally
Muscles: represented vertically
Correlation Values: Spearman Rho correlations
(* significant p<.01)

muscle Tibialis Anterior (TA). Subsequent to this initial distal activity, a time region of mixed activation of both proximal and distal muscles was noted: the plantarflexor Soleus (SOL), the knee extensor Vastus Lateralis (VL), and the knee extensor/hip flexor Rectus Femoris (RF). Activity in the knee flexor/hip extensor muscle Biceps Femoris (BF) was initiated either at landing or during the postlanding phase.

The **Transitional Pattern** was characterized by a global shift of muscle onsets toward landing coupled with the loss of a clear distinction in the intermuscle activation pattern, as the onsets tended to be similar. The TS pattern was initiated distally with activity in the LG muscle. As in the AS pattern, this distal activity was followed by a mixed activation of the distal and proximal muscles SOL, VL, and RF. The onset of these muscles tended to be coincident as the mean onsets for all three muscles occurred within a 24 ms window. The remaining distal muscle TA was activated together with the BF muscle during the final phase of flight. Interestingly, in this pattern, the 95% confidence interval limits for the onsets of all muscles never extended into the postlanding phase of the jump.

The **Proximal-distal Pattern** was primarily defined by a reversal in the muscle activation sequence from that of the AS pattern thereby yielding a proximal-to-distal sequence of muscle onset referenced to landing. The PDS pattern was initiated proximally with activity in the VL muscle. Subsequent to this proximal activity, two regions of mixed proximal and distal activity were noted; the first involved activity in the TA and RF muscles, while the second involved activation of the SOL and BF muscles during the final phase of flight. In contrast to both the AS and TS patterns, activity in the distal muscle LG was typically initiated during the postlanding phase of the jump. In fact, the 95% confidence limits for all three distal muscles extended into the postlanding phase, a feature that was never observed in either the AS or TS patterns.

Frequency Distribution for the Muscle Onset Patterns: The frequency distribution for the three muscle onset patterns across all individuals is illustrated in Table (3). Based on the dominance of one pattern of muscle activation across trials, individuals were classified into one of three corresponding classification groups: the Adult Pattern group, the Transitional Pattern group, and the Proximal-distal Pattern group. For example, one child (VC) was assigned to the Adult Pattern group since the Adult muscle onset pattern was observed on 88% of trials. Similarly, the subject LF was classified into the Transitional Pattern group since the Transitional muscle onset pattern was adopted on 86% of the trials. In this manner, one subject (VC) was classified into the Adult Pattern group, while three subjects (LF, JV, and MPC) were assigned into the Transitional Pattern group and the remaining five subjects (DPC, FS, JND, FB, and MR) were placed into the Proximal-distal Pattern group. The trial sequence for each landing pattern across all individuals is indicated in Table (3). The trial distribution revealed a tendency for individuals to alternate between muscle onset patterns on different trials. However, a systematic correlation between the trial sequence and the type of muscle onset pattern was not observed. In none of the individuals was one type of muscle onset pattern expressed more consistently in earlier trials and another pattern in later trials. For

TABLE 3

Frequency Distribution for the Landing (EMG) Patterns

Subjects	Distribution of landing patterns	% Trials	Group
VC	AS: 1,3,6,7,8,10 TS: 9	88% 12%	AS
LF	TS: 1,3,5,6,8,9 PDS:10	86% 14%	TS
JV	TS: 4,6,8,9,10 PDS:1,3,5,7	55% 45%	TS
MPC	TS: 1,2,5,6,7,10 PDS:3,4,8,9	60% 40%	TS
DPC	TS: 10 PDS: 1,2,3,5,8,9	14% 86%	
FS	PDS:1...10	100%	PDS
JND	TS:3,10 PDS:1,2,7,8,9	25% 75%	PDS
FB	TS:7,8,9 PDS:1...6,10	30% 70%	PDS
MR	AS:1 TS:7,8,9 PDS:1,3,5,...9	10% 20% 70%	PDS

Legend: **Subjects:** Identification of the individuals
Distribution: The trial sequence for the 3 EMG landing patterns: AS, TS, and PDS.
% Trials: The percent number of trials for each of the 3 EMG landing patterns.
Group: Identification of the individuals in each of the 3 classification groups.

example, for the Transitional group individual MPC, the TS pattern was observed in both early (1 and 2) and later trials (7 and 10), with the PDS pattern similarly being observed in both early (3 and 4) and later (8 and 9) trials. Therefore, an effect of trial sequence on the type of muscle onset pattern adopted for landing was not discerned.

The pattern of muscle activation for landing therefore appeared to be a useful tool for classifying individuals into specific groups In order to explore the validity of this EMG-based classification, the kinematic profiles associated with each of the three classification groups were investigated The kinematic analysis focused on differences in the organization of the joint and muscle parameters during flight and the resultant postlanding stability profiles.

4.3 Variability Profile Analysis.

The variability profile was established to examine the organization of the movement in the joint position domain during flight across trials. The variability profiles for the hip, knee, and ankle joints are illustrated in Figure (7) for one representative individual in the AS, TS, and PDS classification groups. In this graph, time regions of decreased variability (< 30% of maximum variability interval) are indicated by 'hatched' time areas while regions of increased variability (> 70% of maximum variability interval) are indicated by 'open' time regions A summary of the variability profiles for all individuals is represented in Figure (8). 'filled' bars correspond to time regions of critical decrease in position variability and 'open' bars to time regions of critically increased position variability.

For the AS individual, the variability profile at the hip joint presented three time regions of increased joint position variability: at the initiation of flight (0% to 10% flight), during midflight (37% to 67%), and during the final phase of flight to landing (83% to 100% flight). A similar variability profile for the hip joint was noted for one TS group individual (MPC). In contrast, the profile for the remaining two individuals in this group (LF and JV) was defined by only two regions of increased variability: at the initiation of flight (0% to 27% flight) and during midflight (33% to 83% flight). No critical modulation of the hip position variability was evident during the final phase of flight to landing A similar absence of variability modulation during the final phase of flight was noted for the three younger PDS individuals, DPC, FS, and JND. The PDS profile in these children was differentiated by a general increase in variability which typically extended through portions of the initial and midflight phases and ending during the final phase of flight to landing (0% to 95% flight for the representative individual). The hip variability profile for the two older PDS individuals (FB and MR) presented a region of increased variability which extended from midflight to landing.

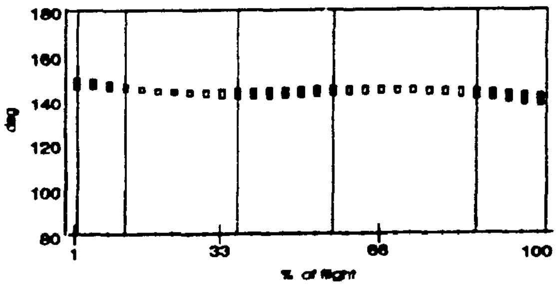
A more evolved pattern of variability modulation was observed at the knee joint. The profile for the AS individual was characterized by a region of increased variability during midflight (30% to 57% flight) and a bi-directional modulation of joint position variability during the final phase of flight. The bi-directional phase included a region of decreased variability (73% to 80% flight) followed by a region of increased variability extending to landing (90% to 100% flight). In the TS group, the profile typically incorporated a region of increased variability during the midflight phase (30% to 57%

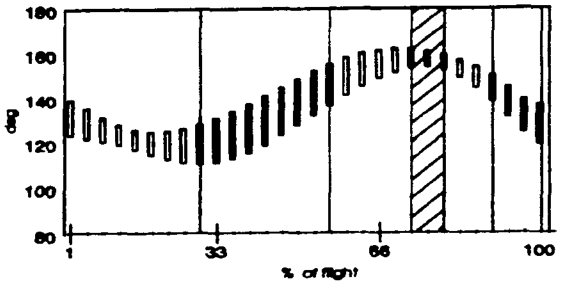
flight for the representative individual). In contrast to the AS profile, a uni-directional modulation of the position variability was observed during the final phase of flight. However, the direction of the variability modulation over this region was not consistent across the individuals in this classification group. In two individuals (LF and JV), a decrease in position variability was noted during the final phase, extending to landing for the individual LF. Conversely for MPC, an increase in variability was observed over this region that extended until landing. In contrast to both the AS and TS profiles, there was an absence of variability modulation during the final phase of flight across both the younger and older individuals in the PDS group. Typically, the PDS profile was defined by a single region of increased variability during the midflight phase (20% to 67% for the representative individual).

The AS profile at the ankle joint was also defined by a bi-directional modulation during the final phase of flight: a region of decreased variability (70% to 80% flight) followed by a region of increased variability extending to landing (90% to 100% flight). An absence of critical variability modulation during the initial and midflight phases was also noted. The TS profile was defined by a region of increased variability through the initial and midflight phases (3% to 57% flight for the representative individual). As observed for the knee joint, the final phase of flight was defined by a uni-directional modulation of the position variability. Again, the direction of this modulation was not consistent across the individuals in this group: a decrease in position variability was noted for LF, while JV and MPC presented an increase in position variability. The region of modulation ended prior to impact for all individuals. In the PDS group, individual rather

Figure 7. The Variability Profiles for the Hip, Knee, and Ankle joints are shown for the representative individual in each of the 3 EMG classification groups: AS, TS, and PDS groups. Takeoff corresponds to 1% on the abscissa and landing to 100%. The minimum variability intervals (< 30%) are indicated in the 'hatched' time regions and maximum variability intervals (> 70%) in 'open' time regions. Joint angle positions are plotted along the Y-axis.

VARIABILITY PROFILE ANALYSIS


ADULT HIP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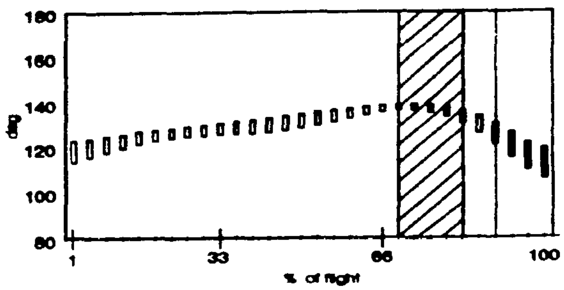
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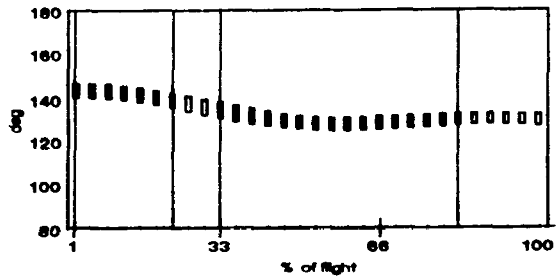
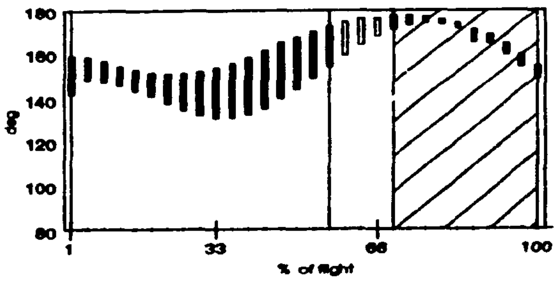

TRANSITIONAL HIP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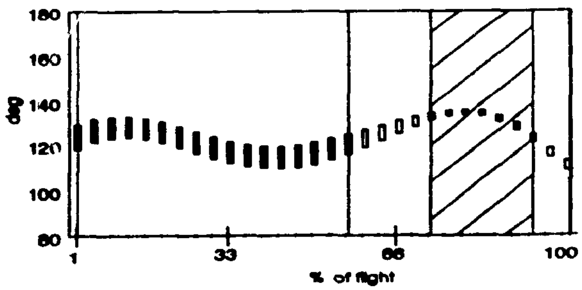
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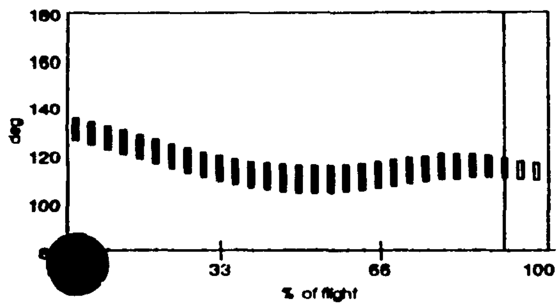
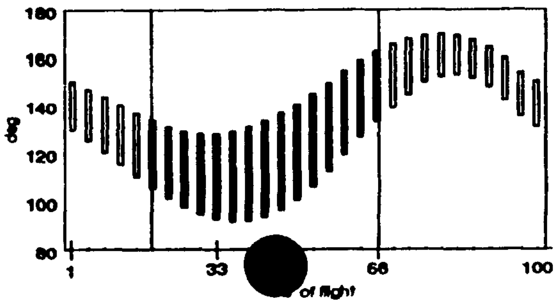

PROXIMAL TO DISTAL HIP


PROXIMAL TO DISTAL KNEE

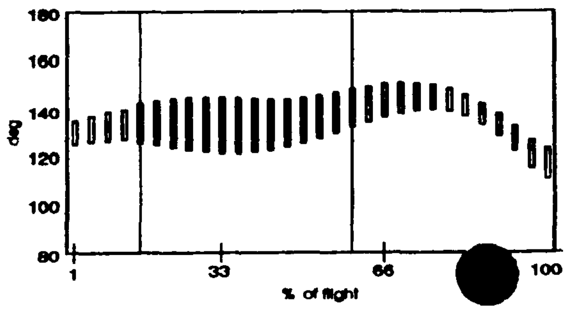
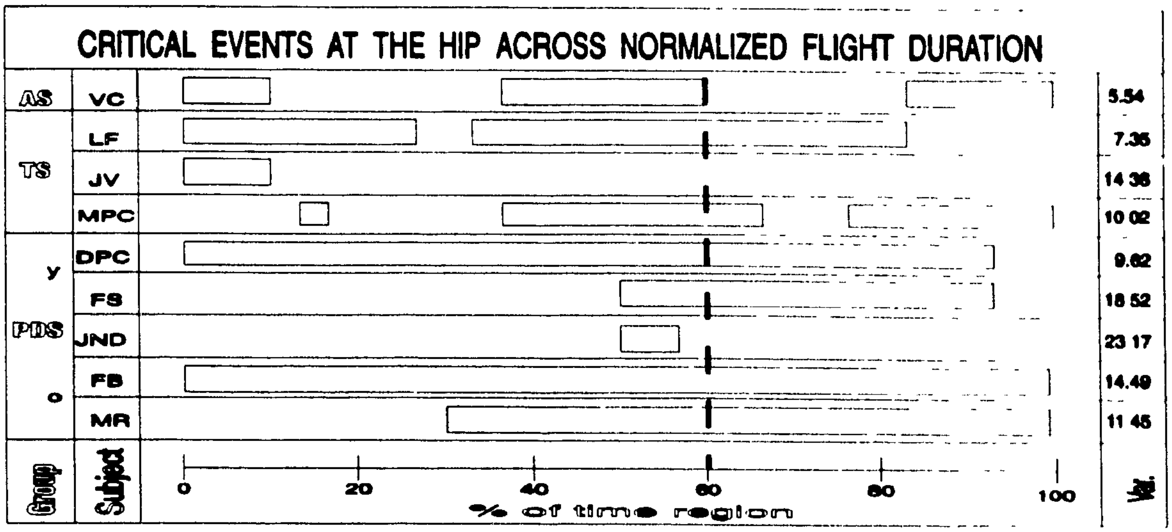
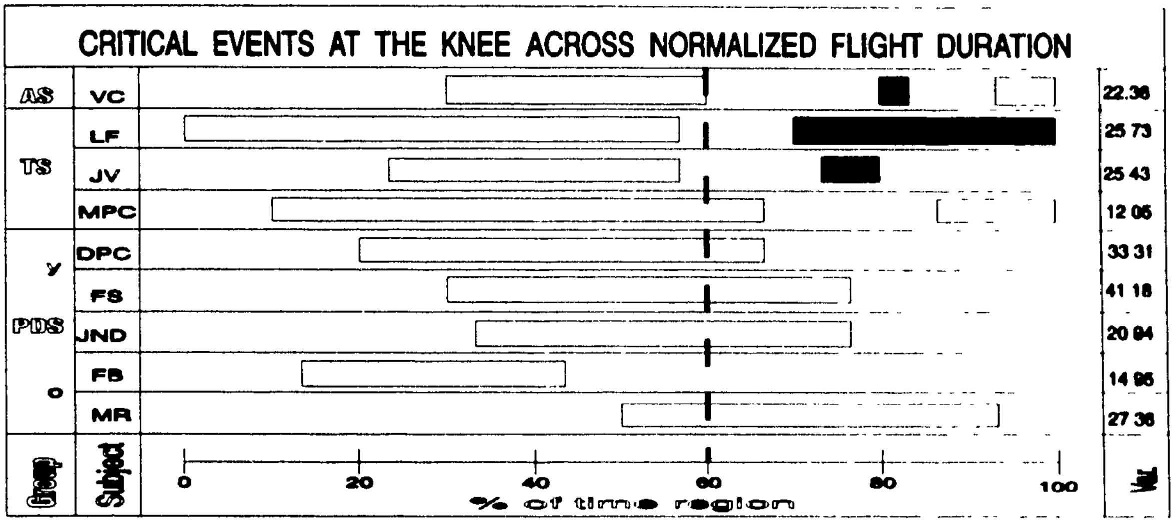

PROXIMAL TO DISTAL ANKLE

Figure 8. The graph summarizes the time profile of the variability profiles at the Hip (A), Knee (B), and Ankle (C) joints across the three EMG classification groups: AS, TS, PDS(y) and PDS(o). The X-axis represents the % of flight from takeoff (0%) to landing (100%). Maximum variability regions are indicated by 'open' bars and minimum variability regions by 'filled' bars. The length of the bars indicates the duration over which the modulation in joint position variability is applied. The dotted vertical line delimits the operational range which is strongly associated with the 3 EMG classification groups.

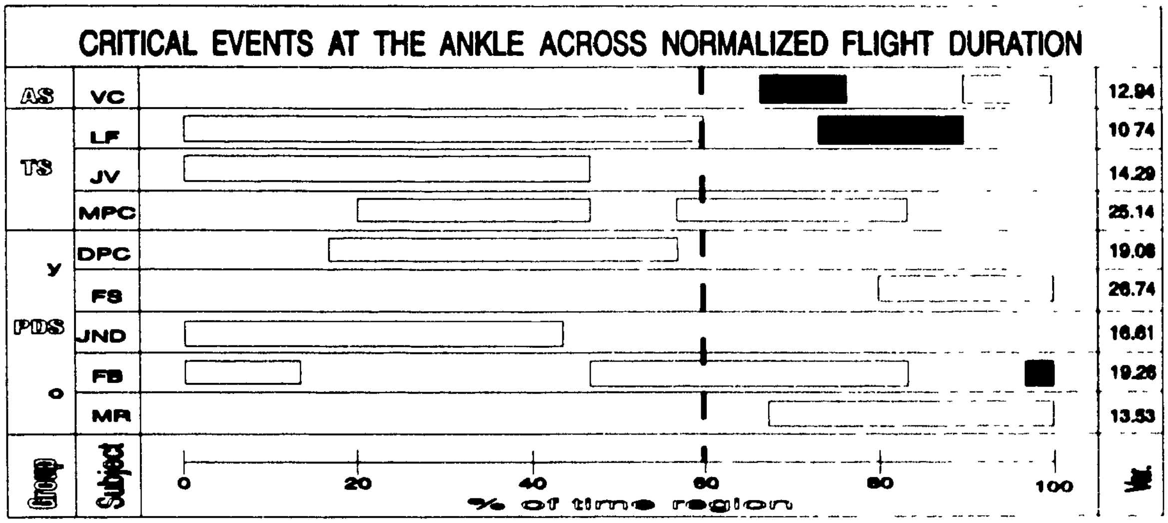
A


CRITICAL EVENTS AT THE HIP ACROSS NORMALIZED FLIGHT DURATION
AS
VC
TS
LF
JV
MPC
y
PDS
o
DPC
FS
JND
FB
MR
5.54
7.35
14 36
10 02
9.62
18 52
23 17
14.49
11 45
Group
Subject
0
20
40
60
80
100
% of time region
Var.

B


CRITICAL EVENTS AT THE KNEE ACROSS NORMALIZED FLIGHT DURATION
AS
VC
TS
LF
JV
MPC
y
PDS
o
DPC
FS
JND
FB
MR
22.36
25 73
25 43
12 05
33 31
41 18
20 94
14 95
27 36
Group
Subject
0
20
40
60
80
100
% of time region
Var.

C


CRITICAL EVENTS AT THE ANKLE ACROSS NORMALIZED FLIGHT DURATION
AS
VC
TS
LF
JV
MPC
y
PDS
o
DPC
FS
JND
FB
MR
12.94
10 74
14.29
25.14
19.08
26.74
16.61
19.26
13.53
Group
Subject
0
20
40
60
80
100
% of time region
Var.

than group differences were observed for the ankle variability profile. Two individuals (DPC and FS) presented a region of increased variability during the initial and midflight phases, coupled with an absence of modulation during the final phase of flight. The remaining younger PDS individual (FS) presented only a region of increased variability during the final phase of flight A similar isolated region of increased variability during the final phase of flight extending to landing was observed in the oldest PDS individual MR. The remaining older PDS individual, FB, revealed a more elaborate variability profile· a region of decreased variability during the initial phase of flight, followed by a region of increased variability during midflight and finally a decrease in variability during the final phase extending to landing

The three EMG classification groups could therefore be distinguished by the modulation of variability in joint position, particularly on the approach to landing. This operational range (delimited by the vertical 'dotted' lines in Figure (8) was more strongly associated with the EMG classification scheme for the knee and ankle joints. The AS profile depicted a bi-directional variability modulation, while a uni-directional modulation was observed for the TS group individuals The PDS profile presented an absence of variability modulation at the knee while a consistent variability could not be identified at the ankle joint As these variability profiles appeared to be an important kinematic feature in the characterization of the three classification groups, differences in other kinematic variables were explored to determine their contribution to the variability profile and also to the organization of the three defined categories of jump-downs.

4.4 Pattern of Joint Reversal for Landing:

Joint preparation for landing was considered as the time at which the last joint reversal occurred prior to touchdown The temporal organization of these joint reversals was considered in relation to the previously described EMG-based classification The pattern of joint reversal for all individuals is illustrated in Figure (9) Results indicated that both the sequence of joint reversals and the variability in the timing of the reversals were loosely correlated to the three EMG classification groups

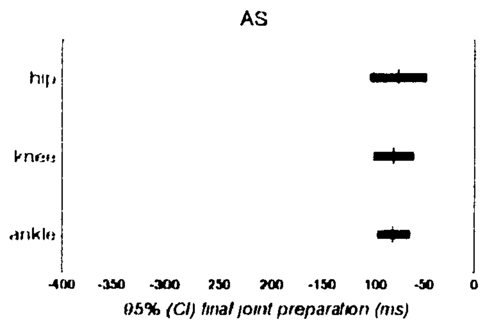
For the AS group subject (VC), the mean joint reversal pattern occurred in a distal to proximal sequence. The sequence was initiated at the ankle (81 ms), with subsequent joint reversal at the knee (-80 ms) and hip (-76 ms) joints However, since all three joints reversed within a 5 ms delay of each other and the 95% confidence interval limits for the timing variability overlapped, the joint reversals were considered to be coincidental in the AS pattern. The largest timing variability was noted for the hip joint (95%CI= 55 ms), the last joint to reverse motion in this pattern, while the timing variability was comparable at the knee (95%CI= 38 ms) and ankle (95%CI= 31 ms) joints. Another salient feature of the profile was the late timing of the joint reversals, the mean reversal occurring within 80 ms of landing at all three joints

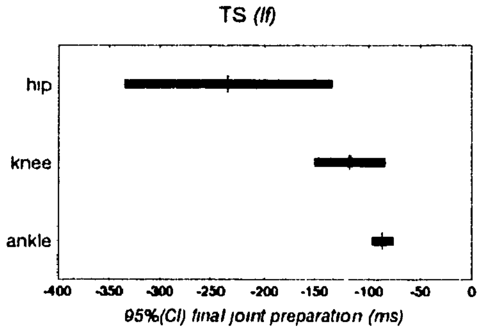
For both the TS and younger PDS classified individuals, the sequence of joint reversal was typically initiated in one of the two more proximal joints early in flight, the range of the timing for the initial joint reversal ranging from (-335 ms) to (101 ms) for the TS individuals and (-364 ms) to (-159 ms) in the younger PDS individuals Typically, significant timing differences were noted for the joint reversal pattern as follows 1) In the TS group, significant differences were noted between the joint reversals at the hip, and at the knee ($p < .05$) and ankle ($p < .01$) for LF, and at the hip, knee ($p < .05$) and ankle ($p < .05$) joints for MPC; and 2) In the PDS group, significant differences were noted at all three joints ($p < .01$) for DPC, at the knee and ankle ($p < .05$) for FS, and between the hip, the knee ($p < .01$) and ankle ($p < .01$) joints for JND. Furthermore, the highest timing variability was noted for the first joint to reverse. Thus, while some TS subjects had in common with the AS subject large variability in the timing of hip reversal, the sequential order of the hip reversal was inverted. Typically, the pattern of joint reversals was such that there was either a difference between the first joint reversal and the other two joint reversals (see MPC) or a significant difference at all three joints (see DPC). These timing differences were seen equally among both the TS and younger PDS groups and thus did not distinguish clearly between the two groups.

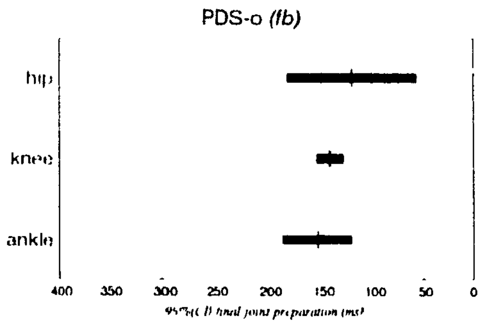
The two older PDS individuals presented final joint reversal patterns which differed from the younger PDS group One individual (FB) presented a profile similar to the AS individual, the ankle initiating the joint reversal pattern with subsequent reversals at the knee and hip joints. The timing of the pattern ranged from (-153 ms) for reversal at the ankle to (-119 ms) at the knee, with the highest variability being noted for the hip joint, the last joint to reverse in the pattern. Again, the confidence interval limits overlapped such that no significant differences were noted across the three joints. The other individual in this group (MR) presented a distinct profile: the joint reversal pattern was initiated at the knee joint (-159 ms) followed by joint reversal at the hip (-121 ms), while reversal at the ankle was delayed close to landing (-28 ms). The timing differences

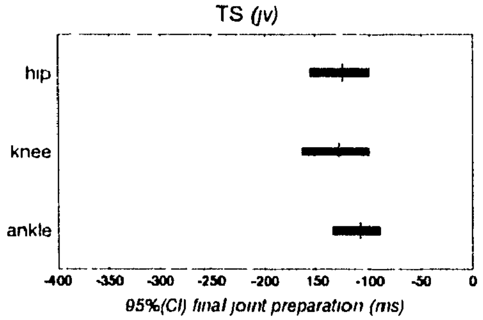
Figure 9. This series of nine (9) graphs represents the means and 95% Confidence Intervals for the time of final joint reversal during flight at the hip, knee, and ankle joints across the 10 trials for each individual. Subjects are categorized by the EMG-based classification: AS, TS, PDS(y), PDS(o).

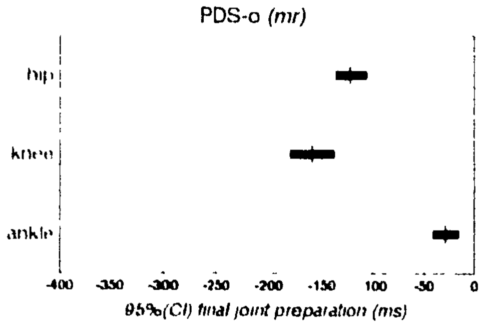
Pattern of Final Joint Reversal

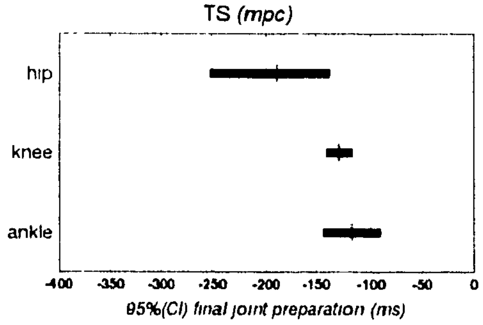




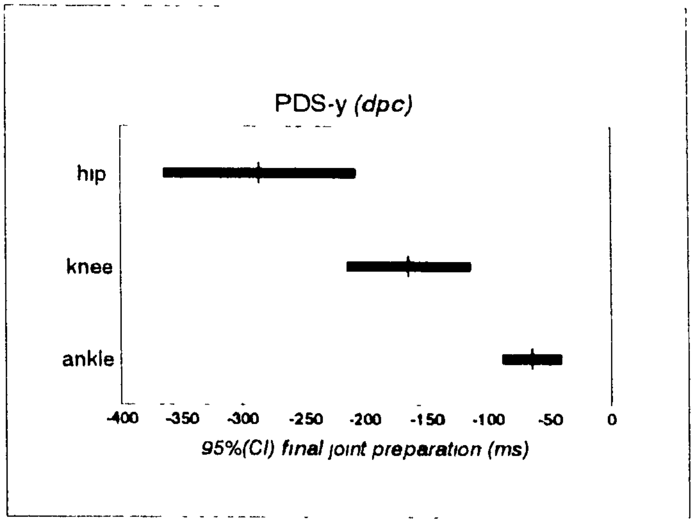


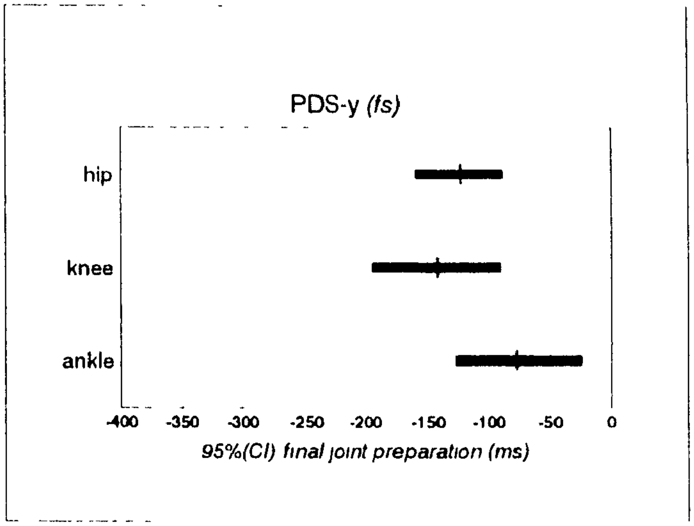


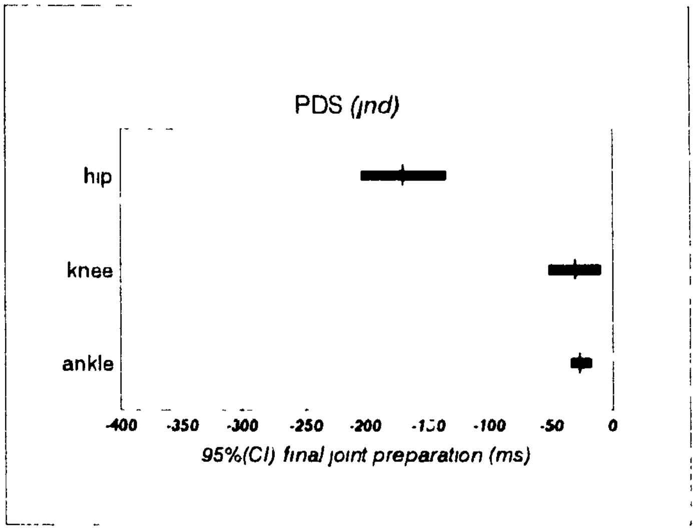




Pattern of Final Joint Reversal







for the reversals were significant ($p < .01$) between all three joints.

4.5 Dynamic Range of Motion:

Dynamic range of motion specifically refers to the absolute joint excursion used at the hip, knee, and ankle joints to organize the movement pattern during flight rather than to the physiological range of motion. Two facets of the dynamic range of motion were addressed: the **central tendency position** and the **operating range**. The central tendency position was defined as the position in the flexion/extension plane around which the joint operated during flight. The central tendency positions for all individuals are illustrated in Figure (10). This position value was approximated by iteration: the mean joint position was established for each 1% interval across the normalized flight and the grand mean of these iterations was used to obtain the overall central position for each individual. The operating range refers to the joint excursion around the central tendency position as well as the variability in the flexion and extension limit positions. Individual operating ranges are illustrated in Figure (11).

For the central tendency position profile, the most extended hip position was observed for the AS individual (VC) at 144° ($p < .01$) and was associated with the narrowest hip operating range 10° ($p < .01$). The maximum hip extension position was coupled with intermediate central positions at the knee (137°) and ankle joints (129°). Intermediate operating range values were also noted for the knee (47°) and ankle (28°) joints in this profile.

The central tendency position and operating range profile for the TS individuals contrasted the AS profile. A more flexed central hip position was noted in the TS group, reaching maximum flexion values in two individuals, JV (108°) and MPC (111°). This hip flexion position was associated with intermediate operating range values for LF and JV, and maximum range for MPC (32°). Maximum extension values were observed for the central position at the knee (155° to 158°; p<.01), while the ankle presented intermediate ankle plantarflexion central positions (124° to 133°). The operating range tended to the maximum at both the knee (37° to 43°) and ankle (25° to 41°) joints

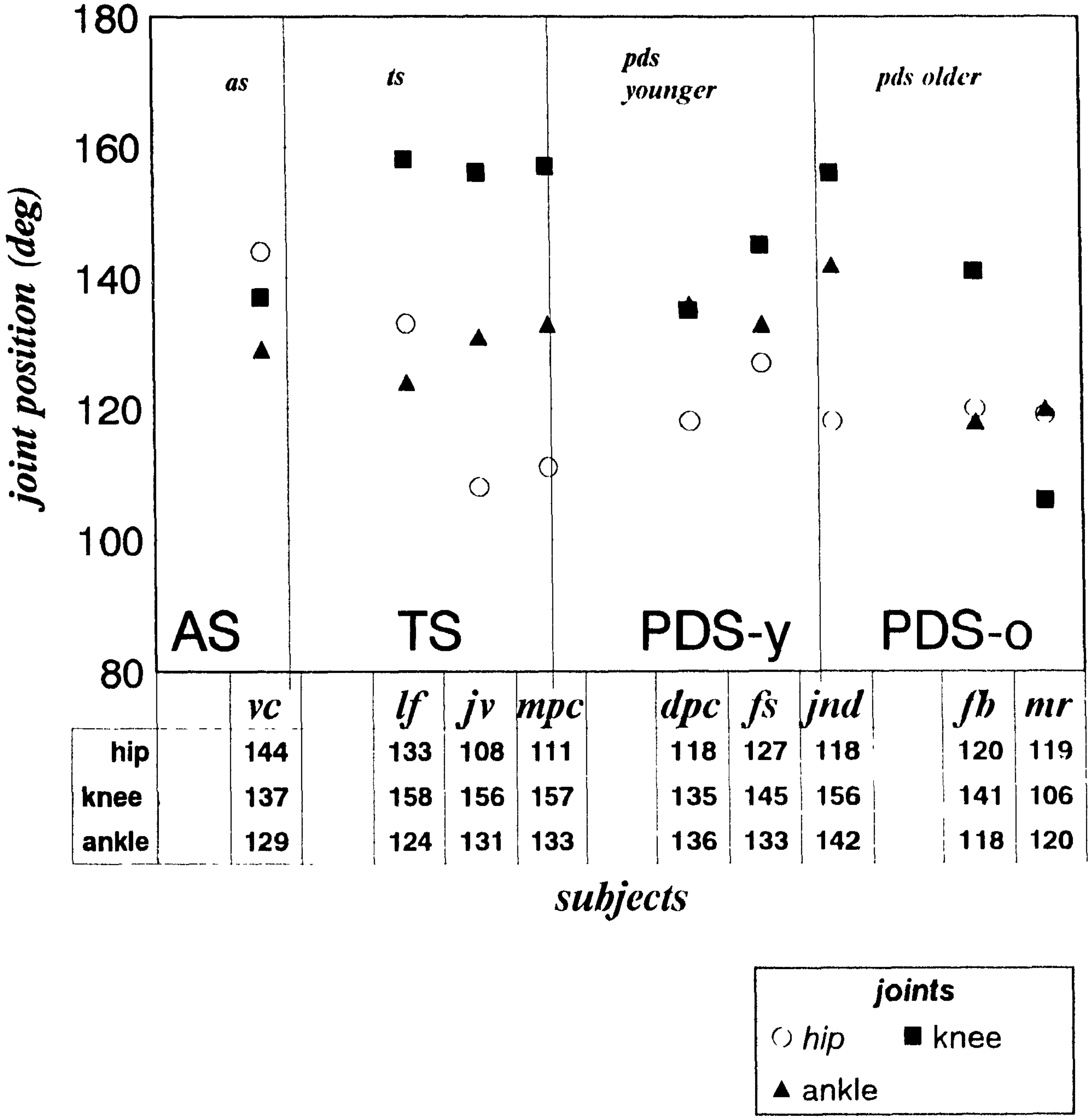
For the three younger PDS individuals (DPC, FS, and JND), the central tendency position profile was defined by an intermediate flexion position at the hip (118° to 127°), greater knee extension than the AS individual (136° to 156°) and for the central position of the ankle maximum plantarflexion values (133° to 142°) The operating range values tended to a maximum for the hip joint (20° to 26°), while the range tended to a minimum for the knee (33° to 38°) and ankle (21° to 26°).

The two older individuals in this group (FB and MR) were unique in that they displayed the most dorsiflexed central ankle position: 118° for FB and 120° for MR. This dorsiflexed position was associated with a large operating range for FB (35°) and a minimum range for MR (13°). The knee joint was in a position of maximum flexion position for MR (106°; p<.01) and intermediate extension position for FB (141°). The operating range values was a maximum for both individuals, 43° for FB and 52° for MR The hip was in a moderately flexed position for both individuals, 120° for FB and 119° for MR. The operating range at the hip tended to a minimum in these individuals, 12° (FB) and 23° (MR).

Figure 10. Mean joint placement during the flight phase: joint positions are denoted in degrees along the vertical axis, 180° representing full extension. (Conventions as in legend for the hip, knee, and ankle joints).

Dynamic Range of Motion

Central Tendency Positions



	vc	lf	jv	mpc	dpc	fs	jnd	fb	mr
hip	144	133	108	111	118	127	118	120	119
knee	137	158	156	157	135	145	156	141	106
ankle	129	124	131	133	136	133	142	118	120

Another differentiating feature of the operating range across the three EMG classification groups was the control of the flexion and extension limit positions across trials This control of limit positions are represented with error bars in Figure (11). The consistency of these limit positions was defined by the standard deviation of the maximum flexion and extension limits for all trials and therefore represent the maximum joint positions observed on any one trial.

In the AS individual, the narrow operating range at the hip joint was associated with a higher variability in the position of the flexion limit (sd = 10°) as compared to the extension limit position (sd = 3°). The extension limit position was at 149° and therefore was not constrained by the biomechanical limit of the hip joint. At the knee joint, consistent positions were noted for the flexion (sd = 3°) and extension (sd = 5°) limits. For the ankle joint, the plantarflexion limit demonstrated a minimum of variability (sd = 2°), as perhaps the PF limit position (139°) could biomechanically constrain this position. In the TS group, limit position variability at the hip joint was comparable to the AS profile, ranging from 3° to 7° for the extension limit and 4° to 5° for the flexion limit Conversely at the knee, a high consistency in the extension limit position was noted, particularly for two individuals LF (2°) and MPC (3°). However, the shift in the operating range toward the biomechanical limit position would constrain the extension limit position. Interestingly at the ankle, both the DF and PF limit positions were consistent across trials despite the operating range being close to the PF biomechanical limit. The DF limit position variability ranged from 2° to 5°. The younger PDS individuals presented a similar profile for the knee joint, the consistency in the extension limit position increasing as the biomechanical limit of this joint was approached. For example, variability in the limit position was a minimum (6°) when the limit position was at 177° (JND) and a maximum (37°) when the extension limit position was at 143° (DPC) The variability in the flexion limit position was relatively high regardless of the limit position, ranging from 9° (JND) to 14° (DPC). A moderate variability at the ankle, similar to the hip joint, was noted for both the flexion and extension limits, values ranging from 5° to 6° for the flexion limit and 6° to 13° for the extension limit.

Interestingly, in the older PDS individual MR, the operating range was biased toward greater knee flexion and yet both limit positions were relatively stable across trials (sd= 11° for both the flexion and extension limits) In contrast for FB, the operating range was shifted into extension and was associated with a decrease in the extension limit position variability, 4° for the extension limit and 8° for the flexion limit At the hip joint, limit position variability was comparable for both the flexion and extension limit positions in both individual. Also, despite the more dorsiflexed position at the ankle, the variability in limit positions was comparable to the younger PDS individuals.

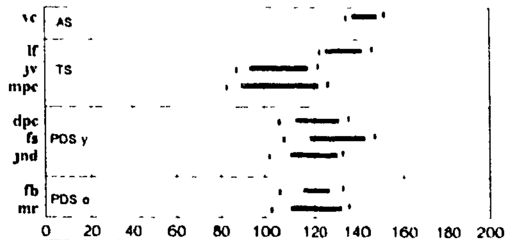
4.6 Movement Organization during Flight:

Joint Coordination Patterns: Joint coordination patterns refer to the time varying organization of joint angle position during flight into meaningful strategies for landing Two distinct organization patterns were identified for the three classification groups and were operationally defined as the **In-phase** coordination pattern and the **Out-of-phase**

Figure 11. Average Range of Motion (horizontal bars) and limit position (error bars) for the: A) hip, B) knee, and C) ankle joints of individual subjects across 10 trials during flight. Error bars at the left represent the maximum flexion position reached on an individual trial while error bars to the right represent the maximum extension on one of the ten trials.

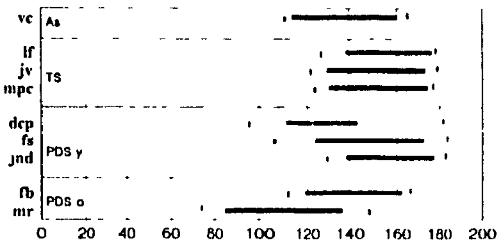
Joint Operating Range

Hip Joint



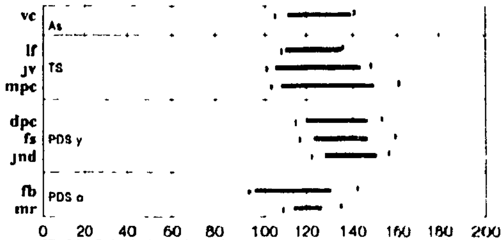
	vc		lf	jv	mpc		dpc	fs	jnd		fb	mr
ext. limit ■	149		143	117	122		132	144	131		127	133
flex. limit ■	139		126	94	90		112	118	110		115	110
sd(ext limit) ■	152		147	122	127		137	148	134		136	137
sd(flex limit) ■	136		123	88	83		106	108	102		106	103

Knee Joint



	vc		lf	jv	mpc		dcp	fs	jnd		fb	mr
ext. limit ■	160		176	173	174		143	172	177		162	137
flex. limit ■	113		139	130	131		110	124	139		119	85
sd(ext. limit) ■	165		178	179	177		182	184	183		166	74
sd(flex. limit) ■	110		127	122	124		96	106	130		111	148

Ankle Joint



	vc		lf	jv	mpc		dpc	fs	jnd		fb	mr
ext. limit ■	139		135	143	149		148	148	150		131	127
flex. limit ■	111		110	105	108		120	124	129		96	114
sd(ext. limit) ■	141		136	148	161		153	158	156		142	135
sd(flex. limit) ■	105		108	101	103		115	117	123		94	109

coordination pattern (Figure 12) This definition was based on the direction of movement at the two joints of a segment In these diagrams (Figure 12, 1-8), flight time durations have been normalized from take-off to landing, and motion at the knee joint is represented along the abscissa while motion at the hip and ankle joints is represented along the ordinate. The rate of change in angle position at the hip and ankle joints is therefore expressed as a function of the rate of change in knee angle position. Reference lines indicate the midposition of the dynamic flexion and extension range at the knee joint (horizontal reference) and at the hip and ankle joints (vertical reference). The intersection of these reference lines was used to define four distinct movement coordination quadrants. For the hip/knee segment, the four quadrants indicated the following movement coordination· 1) In the first quadrant, both joints are in extension above the flexion/extension midrange; 2) In the second quadrant, the hip is in extension above midrange while the knee is in flexion below midrange; 3) In the third quadrant, both joints are in flexion below the midrange reference; and 4) In the fourth quadrant, the hip is in flexion below midrange while the knee is in extension above the midrange. For the ankle/knee segment, the movement quadrants indicated the following: 1) In the first quadrant, the ankle is in plantarflexion and the knee in extension above midrange; 2) In the second quadrant, the ankle is in plantarflexion and the knee in flexion below the midrange; 3) In the third quadrant, the ankle is in dorsiflexion and the knee in flexion below midrange; and 4) In the fourth quadrant, the ankle is in dorsiflexion and the knee is in extension above the midrange

The *In-phase* coordination pattern was defined by a coincident increase or decrease in intersegmental joint angles such that the two joints of a segment either flexed or extended in concert. From this definition, knee flexion would be associated with hip flexion and ankle DF, while extension at the knee would be associated with hip extension and ankle PF. In contrast, the *Out-of-phase* coordination pattern was characterized by a dichotomous increase or decrease in intersegmental joint angles, such that flexion and extension movements occurred in opposition at the two joints of a segment In this coordination pattern, knee extension is associated with flexion at the hip and DF at the ankle, while knee flexion is associated with hip extension and ankle PF In either the *In-phase* or the *Out-of-phase* coordination pattern, a displacement of the resultant movement line along the horizontal or vertical axis indicates a movement isolated to one joint of the segment, the position at the second joint remaining constant

Movement Organization at the Hip/Knee Segment: The movement organization incorporating the *In-phase* pattern at the proximal segment (Figure 12, 1-4) was defined by three movement phases: 1) The first movement phase was initiated from a position of extension greater than midposition at both the hip and knee joints (first quadrant) and proceeded with coincident flexion to a point of maximum flexion at both joints below midrange (third quadrant); 2) Coincident joint reversals into extension initiated the second movement phase, with the subsequent movement proceeding into extension to a point of maximum extension for the knee but not the hip (first quadrant), and 3) The third and final movement phase was initiated with a simultaneous joint reversal followed by coincident flexion directed to the third quadrant for landing An interesting feature of this

In-phase movement organization was the slower rate of angular displacement at the hip joint relative to the knee joint

Further timing differences between the motion at hip and knee joints could effectively 'decouple' the *In-phase* organization over specific epochs of the movement thereby altering the form of the execution pattern. Two stable forms of the 'decoupled' organization were noted 1) In the first movement organization, the *Phase-lag* pattern (Figure 12, 2), the knee reached a point of maximum flexion and joint reversal into extension prior to the hip, such that joint reversal at the hip occurred as the knee was already extending into the second phase of the movement Similarly, at the end of the second movement phase, peak knee extension and joint reversal again occurred prior to the hip, such that the final phase of hip extension and joint reversal occurred as the knee was already flexing in anticipation of the landing; and 2) The second movement organization, the *'Freezing'* pattern, was typified by the cessation of motion at the hip joint early in the movement profile, the hip subsequently maintaining a stable position as the flexion movement at knee joint proceeded in anticipation of landing. As illustrated for a representative trial in Figure (12, 3), a coincident flexion was initially established at the hip and knee joints to a point of maximum flexion. From this point of maximum flexion, a 'freezing' of the hip position was noted such that a stable hip position was maintained during the subsequent two knee reversals, including the final flexion movement in anticipation of the landing.

The second distinct movement pattern at the proximal segment was the *Out-of-phase* organization which was characterized by the presence of the dichotomous coordination pattern during at least one phase of the movement (Figure 12, 4). Typically this movement organization was defined by two movement phases. 1) The movement originated from a position of flexion at the hip and knee joints and proceeded into hip flexion and extension at the knee. This dichotomous proximal flexion and distal extension continued to a point of maximum hip flexion position. 2) A joint reversal at the knee initiated the second movement phase, the flexion position at the hip being maintained within 2° until landing in the representative graph. Consequently, the joint reversal at the knee and the subsequent flexion to landing were associated with minimal adjustments in hip position. This 'freezing' of the hip position was reflected as a horizontal displacement of the resultant movement line to the left during the second movement phase to landing.

Movement Organization at the Ankle/Knee Segment: The classification of the movement organization into distinct *In-phase* and *Out-of-phase* patterns at the distal segment was complicated by the presence of an initial period of dichotomous movement, the ankle plantarflexing as the knee continued its flexion to peak trajectory of the center of mass. As this dichotomous phase was consistent across all individuals and trials, the classification of the movement organization was based on the type of coordination pattern during the remaining phases of the movement.

The *In-phase* movement organization at the ankle/knee segment illustrated in Figure (12, 5) was defined by four movement phases. 1) The movement originated with the ankle in a plantarflexed position and the knee in extension. From this position, the knee proceeded into flexion as the ankle continued to plantarflex, thereby yielding a brief period of dichotomous coordination pattern (10% to 20% flight for the representative trial); 2) The second movement phase was initiated by a joint reversal at the ankle. Subsequent to this point of ankle reversal, an *In-phase* coordination pattern was observed, with coincident knee flexion and ankle dorsiflexion movement to midrange for the ankle; 3) The third phase was initiated through a coincident joint reversal and subsequent coincident extension at the knee and plantarflexion at the ankle to a point of maximum extension in the first quadrant; and 4) From this maximum extension position, a coincident joint reversal was observed followed by a flexion motion at the knee and dorsiflexion at the ankle in anticipation for landing.

A *Phase-lag* organization was also observed for the *In-phase* movement at the distal segment. In this movement organization, the phase-lag was introduced at the point of the first joint reversal initiating the second phase of the movement. The phase-lag movement organization is illustrated in Figure (12, 6). Typically in this phase-lag organization, the knee reached its position of maximum flexion as the ankle was continuing to dorsiflex The maximum knee flexion position was maintained as motion at the ankle proceeded to the point of maximum dorsiflexion. In the representative diagram, the joint reversal at the ankle was lagging the knee by 23% of flight, the knee position remaining stable during this period. This phase-lag was reflected in the displacement of the resultant movement line along the vertical axis from the second to the third quadrant. Subsequently, the coincident movement to the first quadrant was resumed for landing. However, the delay in the movement execution introduced by the phase-lag resulted in the knee being more extended and the ankle more plantarflexed at landing as compared to the other *In-phase* organizations.

The second movement organization observed at the ankle/knee segment was the *Out-of-phase* pattern. This strategy was characterized by the presence of at least one dichotomous movement phase, excluding the consistent dichotomous phase post-takeoff Typically, this movement pattern was organized around a dominant direction of ankle motion through flight. The dominant ankle motion, either into PF or DF, resulted in a relatively independent motion of the knee and ankle joints The PF movement organization is illustrated in Figure (12, 7) and was defined by three movement phases 1) The movement originated in the fourth quadrant with the knee in extension and the ankle in dorsiflexion The initial movement phase presented a dichotomous movement as the knee flexed and the ankle plantarflexed; 2) The second movement phase was initiated by an independent joint reversal and subsequent extension at the knee as the ankle continued to plantarflex; and 3) The third and final movement phase incorporated a coincident joint reversal followed by a knee flexion and ankle dorsiflexion in anticipation of landing. Thus, this strategy was typified by a progressive plantarflexion at the ankle associated with the initial flexion and subsequent extension movement at the knee, followed by a dorsiflexion at the ankle while the knee was flexing for landing

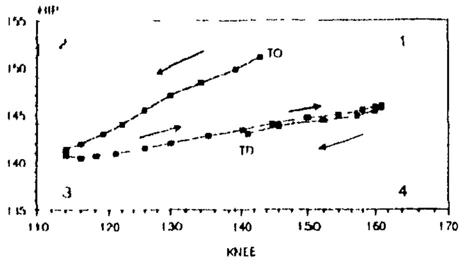
Conversely, the DF movement organization was characterized by a progressive dorsiflexion of the ankle, independent of the distinct movement phases observed at the knee. This movement organization was again defined by three movement phases and is illustrated in Figure (12, 8). 1) The movement originated in a position of ankle plantarflexion and knee flexion in the second quadrant. The initial movement proceeded into ankle dorsiflexion and knee flexion; 2) An independent joint reversal at the knee initiated the second movement, while still in the second quadrant. Subsequent to this joint reversal, the knee extended as the progressive dorsiflexion at the ankle was maintained. This dichotomous movement pattern continued to a point of maximum extension at the knee in the first quadrant, and 3) An independent joint reversal at the knee also initiated the third movement phase This final phase was defined by a coincident motion at the two joints of the distal segment, the ankle continuing to dorsiflex while the knee was flexing in anticipation for landing

The landing phase of the jump-down would primarily be affected by the direction of the joint motion and the accompanied muscle activity during the final phase of the movement organization patterns in anticipation of landing Interestingly, the different movement organizations identified at the proximal segment did not yield different movement directions during the final phase to landing. In the four distinct organization patterns, the hip and knee joints were flexing during the final movement phase in anticipation for landing However, different joint direction movements were associated with the four distinct organization patterns at the distal segment. The *In-phase* and *Out-of-phase (DF)* patterns resulted in a flexion movement at the knee and dorsiflexion at the ankle during the final phase of flight. In contrast, a knee extension movement coupled with dorsiflexion at the ankle during the final phase of flight was associated with the *In-phase (phase-lag)* and the *Out-of-phase (PF)* organization patterns.

Figure 12. This series of eight (8) graphs represents the movement organization at the hip/knee (graphs 1-4) and ankle/knee (graphs 5-8) segments. Flight time durations have been normalized from takeoff to landing and motion at the knee is represented along the abscissa while motion at the hip (1-4) and at the ankle (5-8) is represented along the ordinate. Horizontal reference lines indicate the midposition of the dynamic ROM at the knee, while vertical reference lines indicate the mid dynamic range position for the hip and ankle. The four movement quadrants are labelled from 1 (extension at both joints of a segment) through 4 (extension at the knee and flexion at the other joint) in a counter clockwise direction. Each graph illustrates one representative trial for each of the identified joint coordination patterns.

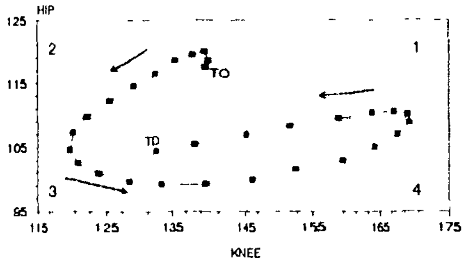
Hip/Knee Interaction Strategies

In Phase *hip/knee*



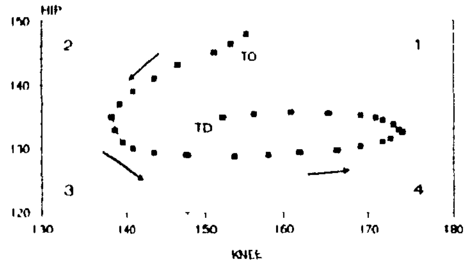
In Phase *hip/knee*

PHASE LAG

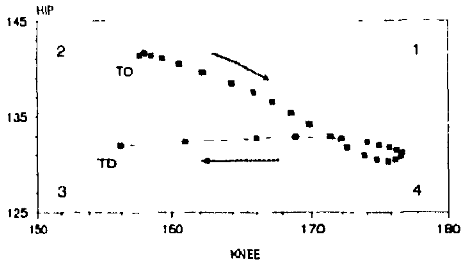


In Phase *hip/knee*

FREEZING

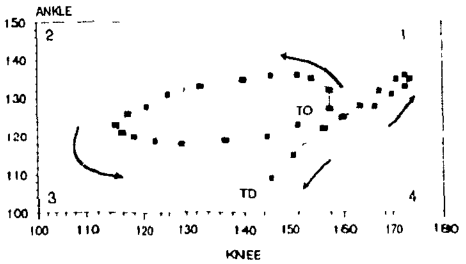


Out of Phase *hip/knee*



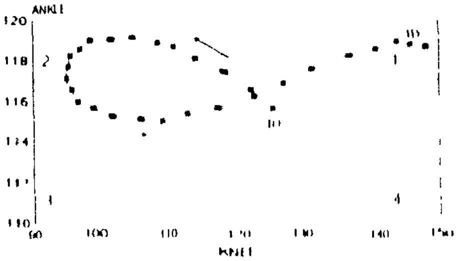
Ankle/Knee Interaction Strategies

In Phase *ankle/knee*

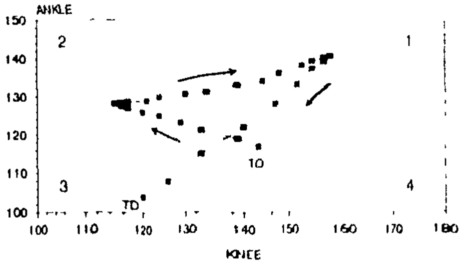


In Phase *ankle/knee*

PHASE LAG



Out of Phase (*pf*)



Out of Phase (*df*)

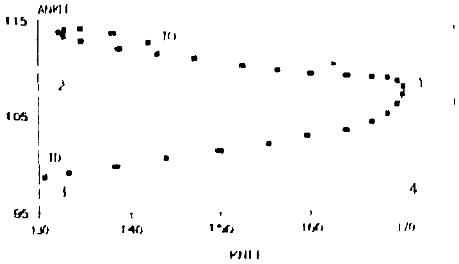


TABLE 4

FREQUENCY DISTRIBUTION FOR THE JOINT COORDINATION PATTERNS

	ANKLE/KNEE		HIP/KNEE	
	In phase	*Out of Phase*	*In phase*	*Out of Phase*
VC	0%	100% PF$^{1-10}$	90% IP$^{1,3-10}$ 10% PL^{2}	0%
LF	100% IP	0%	60% Fr$^{5-10}$	40% $^{1-4}$
JV	10% IP^{3}	90% PF$^{1,2,4-10}$	10% PL^{2} 70% Fr$^{3-6,8-10}$	20% ^{1,7}
MPC	10% IP^{6}	90% PF$^{1-5,7-10}$	20% IP^{2,4}	80% $^{1,3,5-10}$
DPC	40% IP$^{4-7}$	50% PF$^{1,2,8-10}$ 10% DF^{3}	60% Fr$^{1-4,9,10}$ 40% PL$^{5-8}$	0%
FS	10% IP^{5} 70% PL$^{1,3,6-10}$	20% PF^{2,4}	90% PL$^{1-5,7-10}$ 10% Fr^{6}	10% ^{5}
JND	80% PL^{1,4,56,8,10}	20% PF^{5,7}	90% PL$^{1-5,7-10}$ 10% Fr^{6}	0%
FB	0%	80% PF$^{1,2,5-10}$ 20% DF^{3,4}	70% Fr$^{1,2,4-7,9,10}$	30% ^{3,8,10}
MR	40% IP^{1,3,4,6}	60% PF$^{2,5,7-10}$	100% IP $^{1-10}$	0%

Legend:
% : The percent number of trials for each pattern
IP: In-Phase Coordination Pattern
PL: Phase-lag Coordination Pattern
Fr: Freezing Coordination Pattern
PF: Out-Of-Phase (PF)
DF: Out-of-Phase (DF)

Superscript numbers indicate the trial sequence

Frequency Distribution for the Movement Organization Patterns: The frequency distribution and trial sequence for the *In-phase* and *Out-of-phase* movement organization at both the proximal and distal segments was established for the three EMG classification groups and is illustrated in Table (4).

For the AS individual, the *In-phase* organization was exclusively observed at the proximal segment, with one trial being of the *phase-lag* type. This proximal *In-phase* organization was exclusively associated with the *Out-of-phase (PF)* pattern at the distal segment

The *In-Phase* organization at the proximal segment was also dominant for the younger PDS group individuals. However, there was an increased frequency of the *Phase-lag* and *Freezing* patterns of the *In-phase* organization in these individuals. For example, two individuals (DPC and JND) adopted either the *Phase-lag* (40% and 90% respectively) or the *Freezing* (60% and 10% respectively) patterns at the proximal segment. Similarly, in FS, the *In-phase* (90%) or *Freezing* (10%) patterns were observed. A consistent movement organization pattern was not observed for these three individuals at the distal segment as they tended to use either the *In-phase*, *Phase-lag*, or *Out-of-phase (PF)* patterns. Therefore, for DPC, the *In-phase* pattern was observed on 40% of trials, the *Out-of-phase (PF)* on 50% trials, and the *Out-of-phase (DF)* pattern on 10% of trials In contrast, FS dominantly adopted the *Phase-lag* patterns (70%) with 10% of trials being of the *In-phase* pattern, while JND adopted the *Phase-lag* on 80% of trials and the *Out-of-phase (PF)* pattern on the remaining 20% of trials.

Different organizational trends were observed for the two oldest individuals in this group, FB and MR. At the proximal segment for FB, the *Freezing* pattern was dominantly observed (70%) with the remaining three trials being of the *Out-of-phase* type. These two proximal patterns were associated exclusively with the *Out-of-phase* pattern at the distal segment, 80% of the PF pattern and 20% of the DF pattern. For the subject MR, the *In-phase* organization was exclusively observed at the proximal segment as for the AS individual while at the distal segment, either the *In-phase* (40%) or *Out-of-phase (PF)* patterns (60%) were observed with comparable frequency.

The proximal movement organization was unique for the TS group in that the *Out-of-phase* movement organization was expressed more frequently than in either the AS or PDS groups. For example, LF adopted either the *Freezing* (60%) or the *Out-of-phase* (40%) patterns, while MPC adopted the *Out-of-phase* pattern on 80% of trials, the remaining two trials being of the *In-phase* type. For the remaining TS individual (JV), the *Freezing* pattern dominated (70%), with 10% of the *Phase-lag* type and the 20% of the *Out-of-phase* type. Interestingly, the TS individuals were highly consistent in the type of movement organization adopted at the distal segment: LF exclusively adopted the *In-phase* organization, while the *out-of-phase* dominated for JV (90%) and MPC (90%).

As for the EMG patterns previously described, an association between the trial sequence and the type of movement organization was not observed (see Table 4). The trial sequence also failed to indicate an association between the type of movement organization at the proximal and distal segments, suggesting that the movement at the two segments could be independently organized.

4.7 Functional Consequence of the Distinct Movement Organizational Patterns

The joint motion and muscle activity during the final phase of flight in anticipation of landing will directly influence the initial absorption of the impact ground reaction forces. Therefore, a more detailed analysis of the movement profile from the point of final joint reversal to landing was carried out and is presented in the following sections.

Power-Time Profile for the Final Phase of Flight: Power-time profiles were used as a first approximation of the muscle contribution (concentric or eccentric work) to the control of the final phase of flight in anticipation for landing. The power-time profiles were adapted from Enoka (1988). A representative profile is illustrated in Figure (13) for the AS individual. Represented at the bottom right of each series of graphs are the angular positions at the hip, knee, and ankle joints during the final phase of flight, from the time of last joint reversal (t=0) to landing. (As these graphs were not normalized to flight time, the time from joint reversal to landing is variable). The corresponding angular velocity and angular acceleration profiles and power-time profiles are represented in the left column.

To establish the power-time profiles, the scalar quantity of power is approximated by multiplying the two vector quantities during the limb movement: angular velocity and angular acceleration, which is proportional to the force. By convention, flexion movements are associated with negative angular velocity values and extension movements with positive angular velocity values. The mass is factored into the resultant power value.

Positive power values represent time regions where the limb movement is concentrically controlled (power production phase) while negative power values represent time regions where the limb movement is eccentrically controlled (power absorption phase). Thus, during power production, the muscles apply work to the system and conversely, during power absorption, the system applies work to the muscles due to inertia.

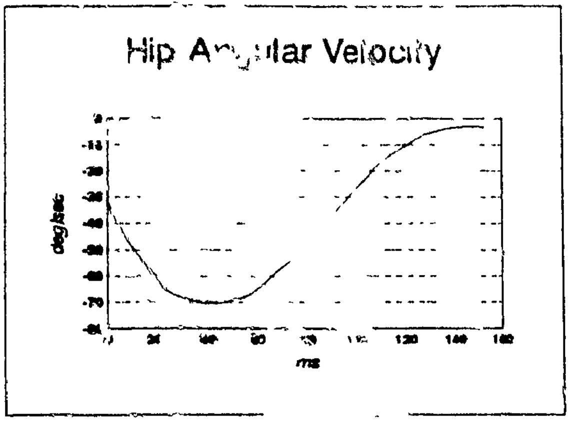
The power-time profiles for all individuals are illustrated in Figure (14, A-I). In these representative graphs, a single trial was illustrated for each individual. To allow intersubject comparison, only trials with similar joint movement organizations were selected. Therefore, for all individuals, the hip and knee joints are flexing toward landing while the ankle is dorsiflexing. Results focused on the interaction of power production and power absorption phases at the three joints, while the quantities of muscle power associated with the movement production is the topic of future investigations.

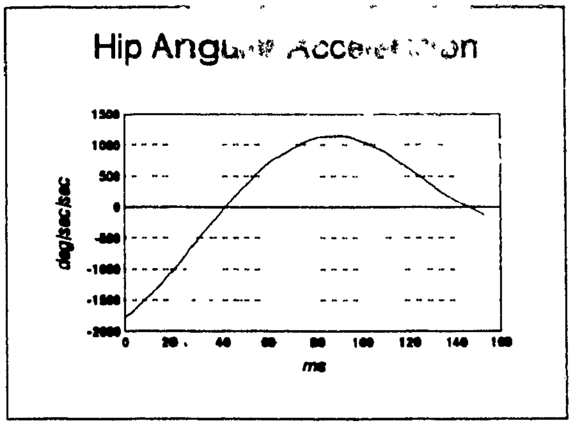
In the AS individual (Figure 14a), power production at the hip was associated with minimal power production at the knee and ankle joints. The power production phase at these two distal joints occurred during the phase of power absorption proximally at the hip joint. At landing, the power absorption phase at the hip was terminated, the power returning to neutral values at impact. Conversely, at the knee and ankle joints, power production decreases gradually during the approach to landing into a phase of power absorption during impact.

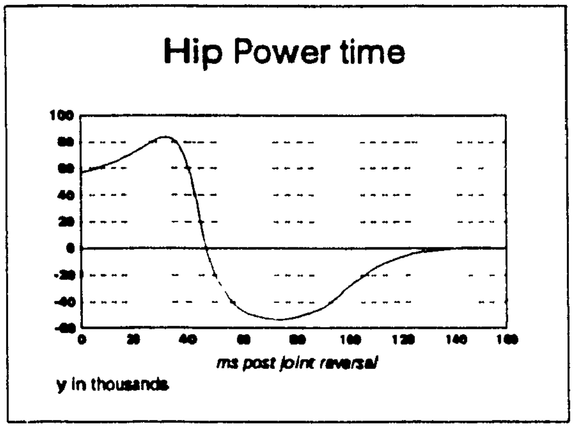
The power-time profiles for the TS group contrasted the AS profile in two aspects: 1) In two individuals, LF and JV (Figure 14b,c), a single phase of power production was observed proximally at the hip joint. This was associated with power

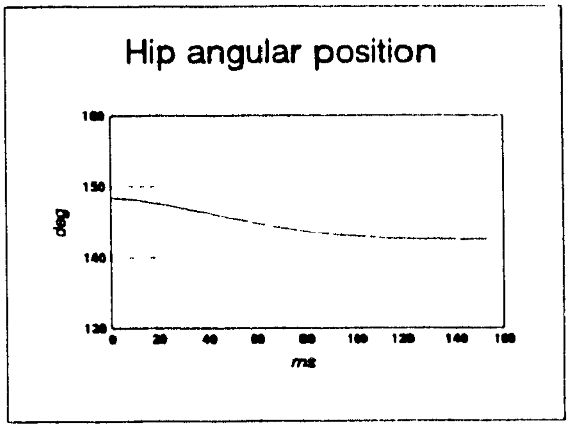
Figure 13. This series of 3 sets of graphs represent the Power-Time Profile for: A) the hip, B) the knee, and C) the ankle Final joint reversals correspond to (t = o) on the abscissa The graphs indicate the multiplicative contributions of the Angular Velocity (top) and Angular Acceleration (middle) to the Power-Time curve (bottom). Flexion movements correspond to negative (-ve) angular velocities. Positive (+ve) power values represent power production phases (concentric muscle work) and negative (-ve) power values represent power absorption phases (eccentric work). The joint angle positions corresponding to the Power-Time profile are illustrated to the bottom right.

Power Time Profile

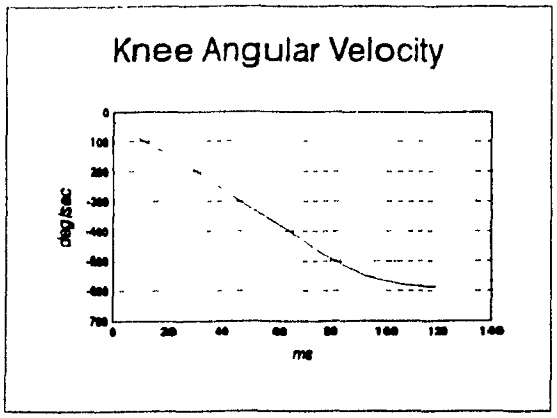

Hip Angular Velocity

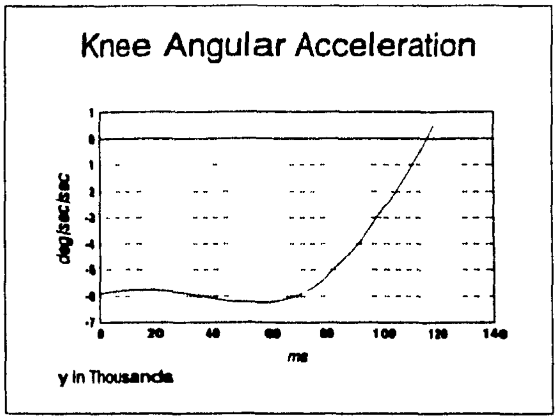

Hip Angular Acceleration

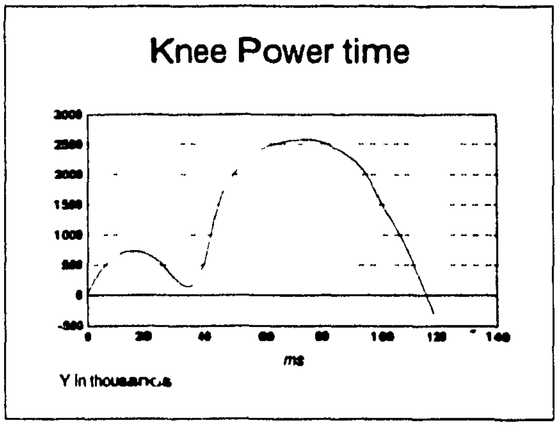

Hip Power time

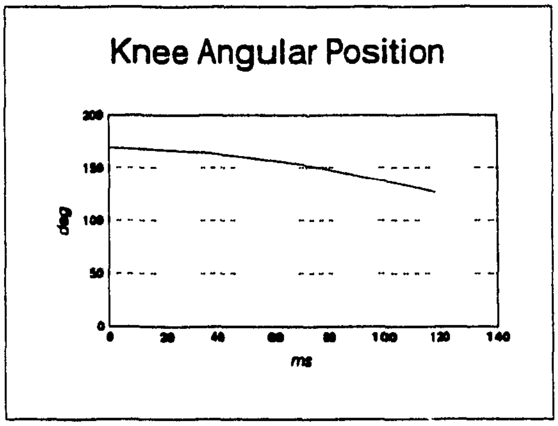

Hip angular position

Power Time Profile

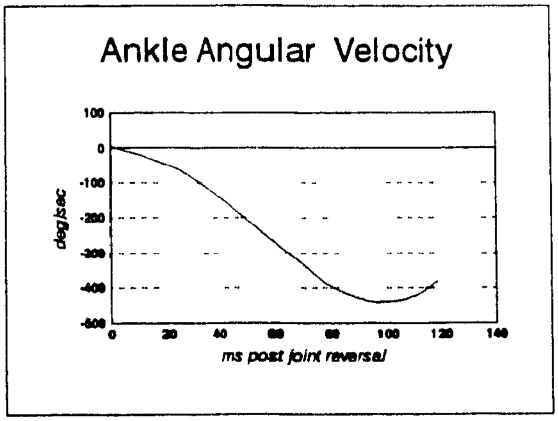

Knee Angular Velocity

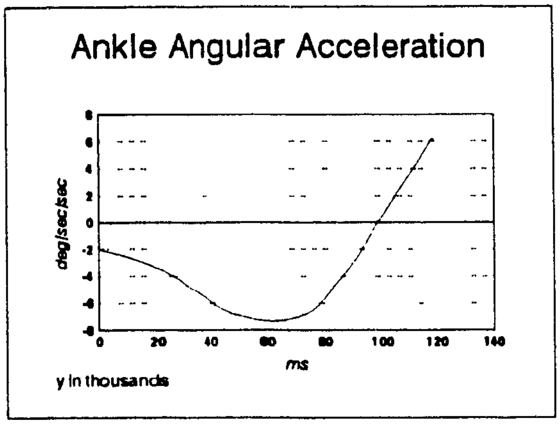

Knee Angular Acceleration

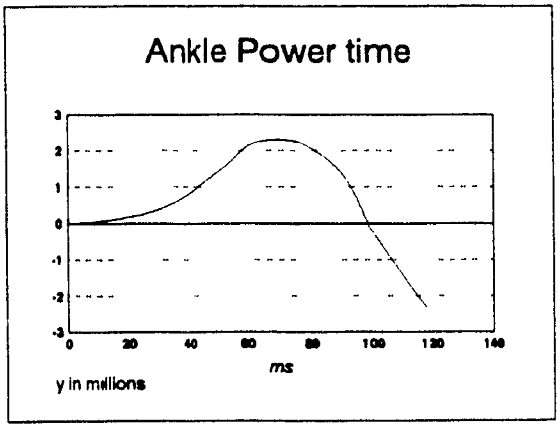

Knee Power time

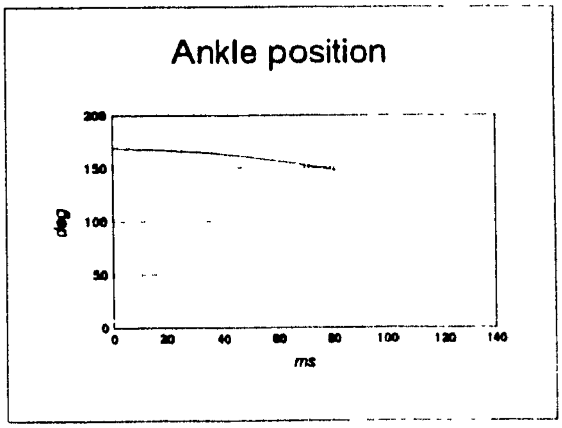

Knee Angular Position

Power Time Profile


Ankle Angular Velocity


Ankle Angular Acceleration


Ankle Power time


Ankle position

production phases at both the knee and ankle joints. Therefore, following joint reversal, all joints are in a power production phase A transition into power absorption for impact is observed at the knee and ankle joints, similar to the AS individual. However proximally, impact was associated with either constant or increasing power production at the hip; and 2) Another power-time profile was noted for MPC (Figure 14d). For this individual, the power production at the hip steadily decreased through the movement into power absorption at impact This was associated with minimal power production phase at the knee At landing, all three joints are in a power absorption phase.

In the younger PDS group, the power-time graphs were unique in two individuals, FS and JND (Figure 14e,f), in that all three joints were in a phase of increasing power production for the impact phase of landing. For DPC (Figure 14g), the power production phase was decreasing for impact, with a transition into power absorption proximally at the hip for impact Also, for the three individuals, the power curves at the three joints mirrored each other during the movement phase, such that power absorption and power production phases were coupled throughout the entire final phase of flight.

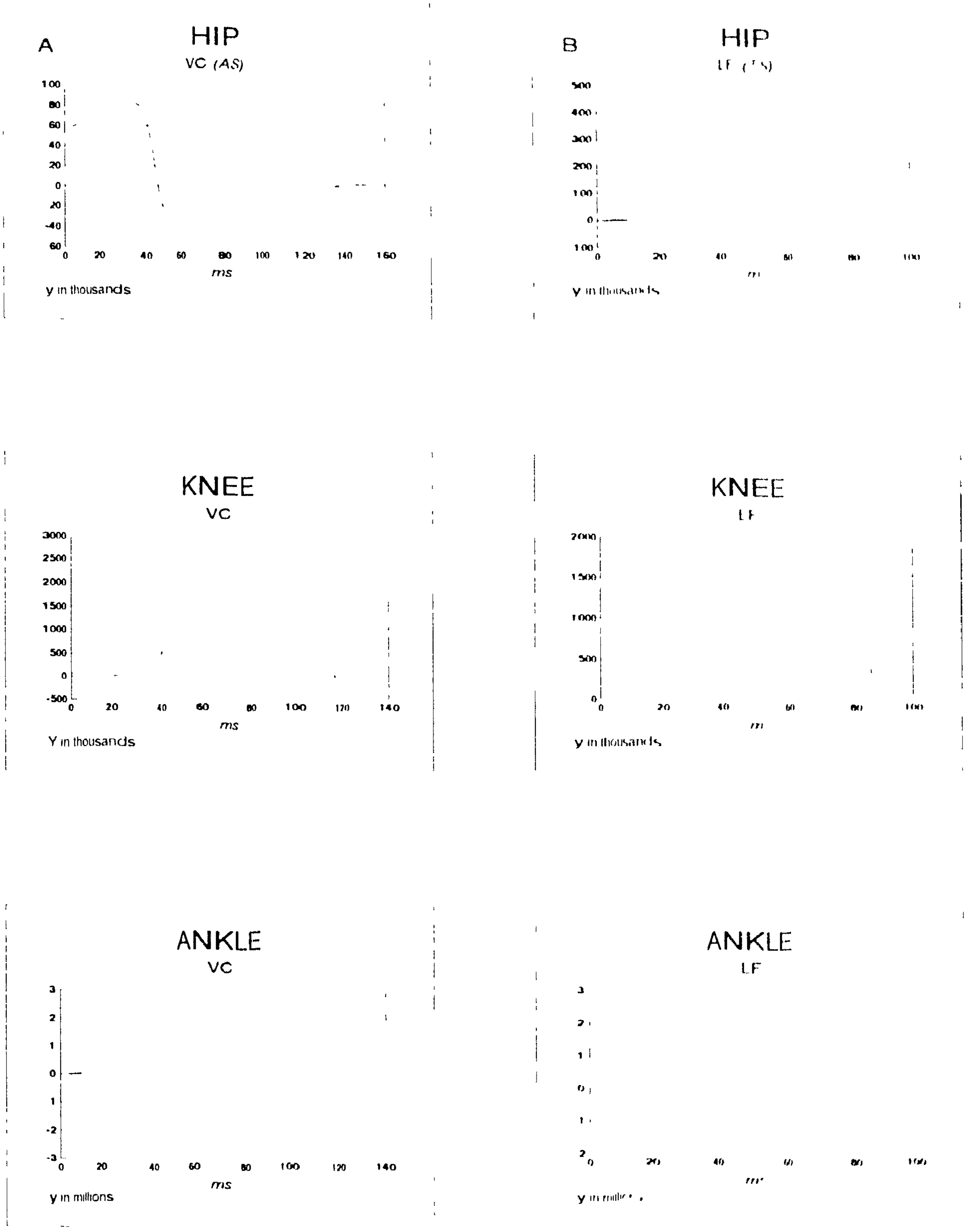
The two older PDS individuals (FB and MR) presented different power-time profiles. The profile for MR (Figure 14h) was similar to the AS individual at the hip and knee joints during the initial phase of the movement, with an initial power production phase at the hip and knee joints In contrast, the ankle presented a phase of power absorption following the joint reversal. However, in contrast to the AS profile, all three joints were in a phase of power absorption during the impact phase of landing. The individual FB (Figure 14i) was similar to the younger PDS individuals in that all three joints were in a phase of power production at impact, the transition from power production to power absorption occurring just prior to landing

Joint Angle Position at Landing: The end-result of the control parameters presented in the previous sections is the specification of the joint configuration at landing. The landing joint angle positions are critical as they dictate the application of the reactive force vector which the system must oppose to maintain stability. The mean (±sd) joint angle positions at landing are listed for all individuals in Table (5). Distinct landing joint position configurations were identified which could be related to the previously established EMG classification groups.

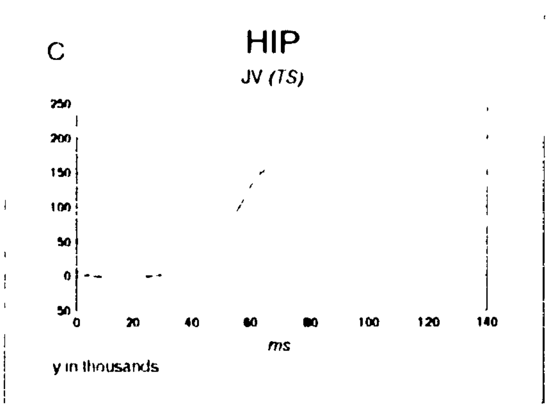
The most extended hip position at landing was found in the AS individual (143°). This hip extension position was coupled with a moderate flexion position at the knee (151°) and PF position at the ankle (131°). In comparison to the AS landing joint configuration, the TS group individuals adopted a more flexed position at the hip (104° to 130°). The knee tended to the extension limit (164° to 175°). Moderate PF positions comparable to the AS individual were observed in two individuals, LF and JV, while MPC used a position of maximum PF at the ankle (147°). Again, in the PDS group, the two older individuals (MR and FB) could be differentiated from their younger cohorts (DPC, FS, and JND) based on the joint position configuration adopted at landing. For the younger PDS group, the hip tended toward the maximum flexion position in two individuals, DPC (118°) and JND (119°), whereas FS adopted a moderately flexed hip position comparable to the AS individual at 132°. Similarly at the knee, the landing

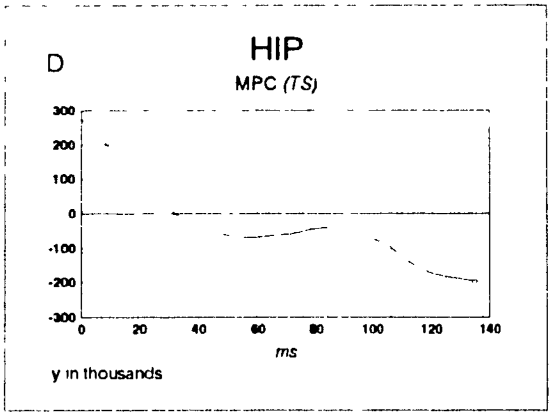
Figure 14. Representative Power-Time Profile for the hip, knee, and ankle joints for all individuals (A-I) categorized according to the EMG classification. All Power-Time curves are associated with the same movement: flexion at the knee and hip joints, and DF at the ankle Real time from final joint reversal (t=0) to landing is shown on the X-axis and power values along the Y-axis.

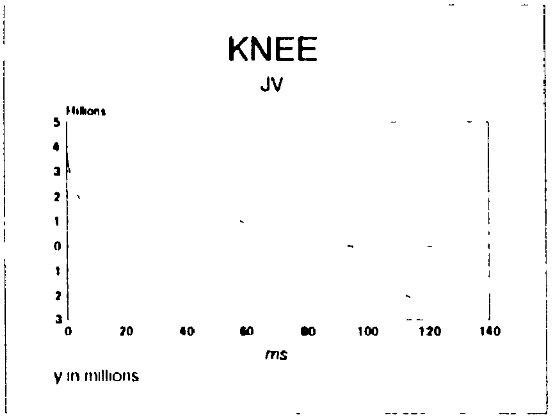
Power Time Profile

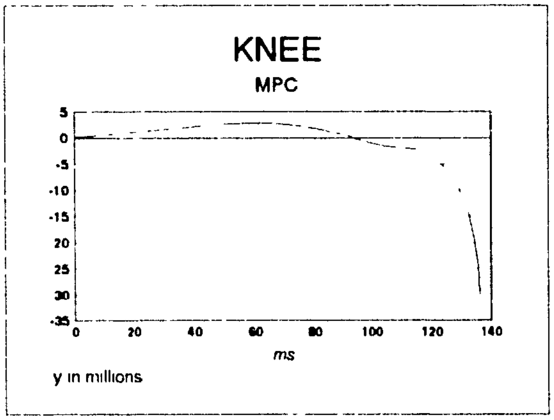


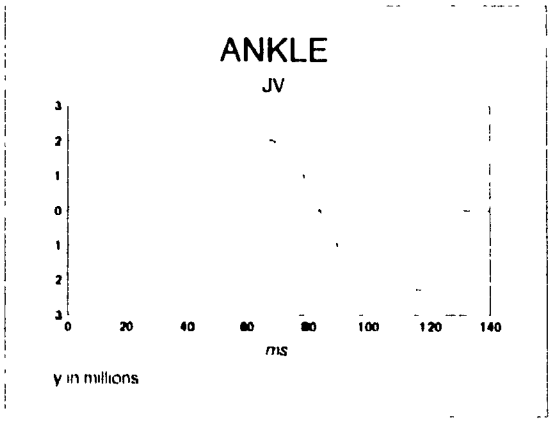
Power Time Profile

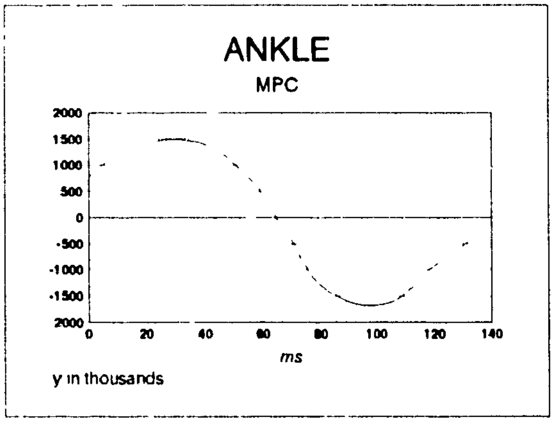












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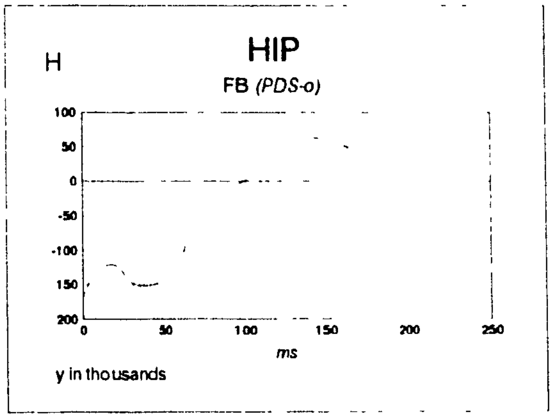

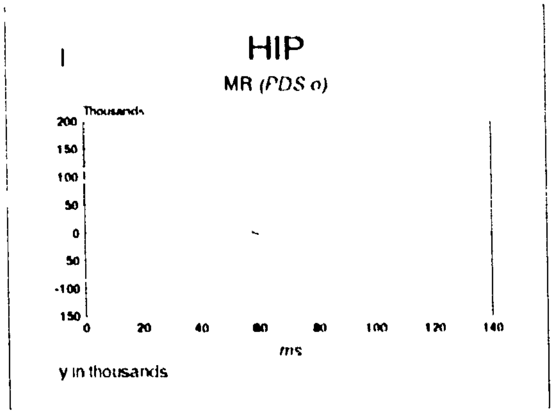

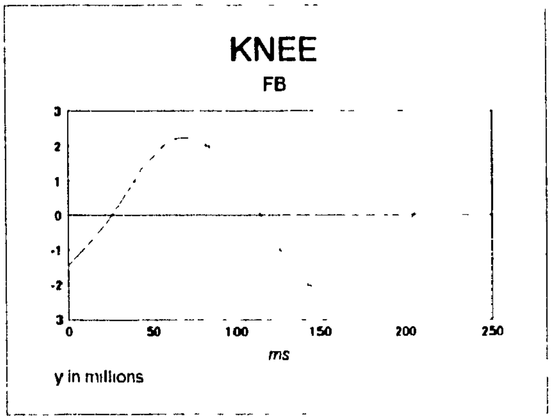

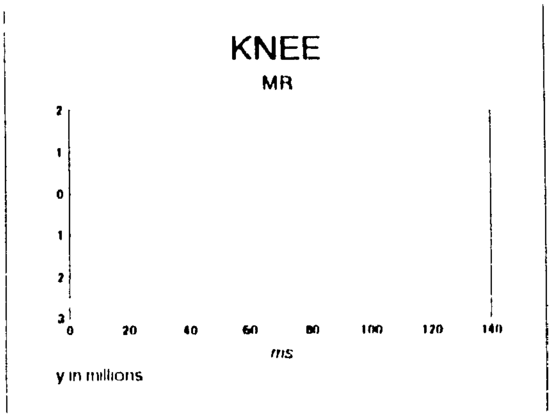

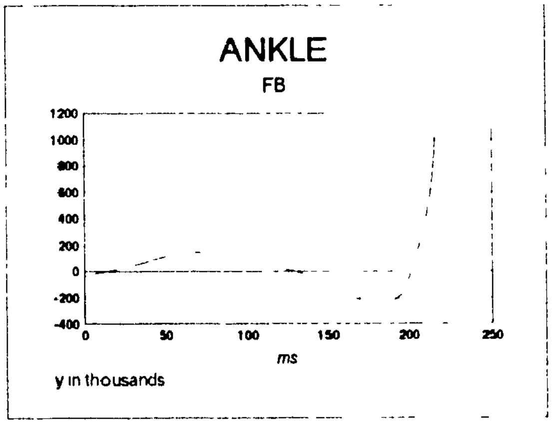

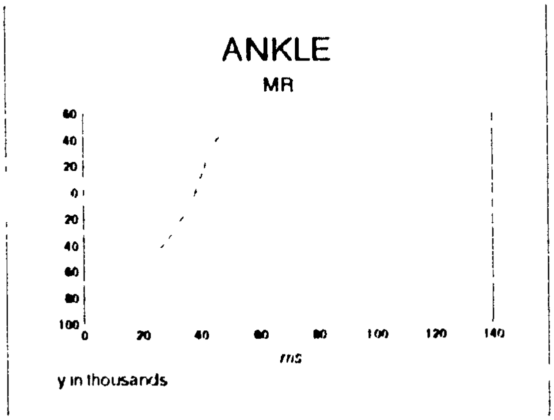

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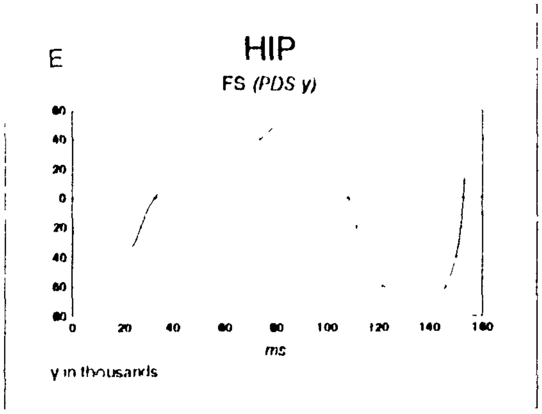
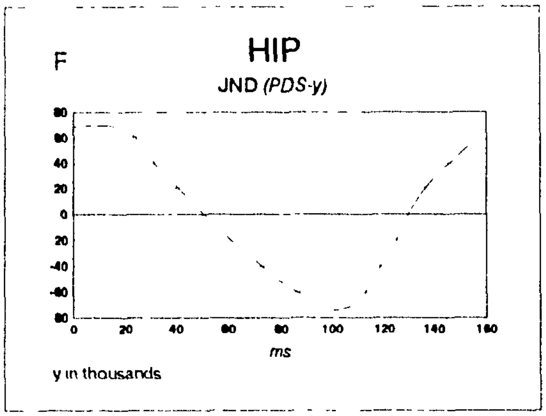

E

HIP

FS *(PDS y)*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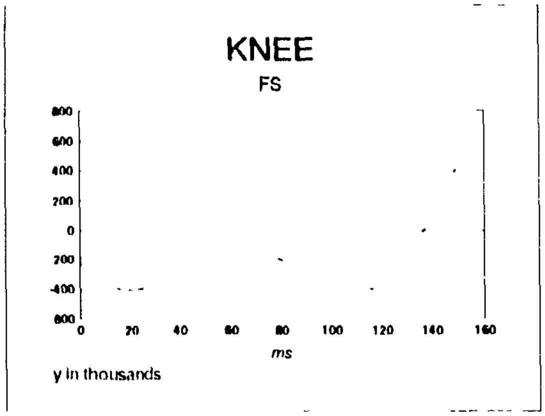
HIP

JND *(PDS-y)*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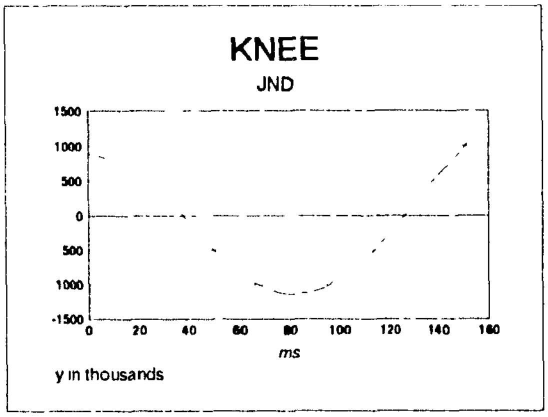
FS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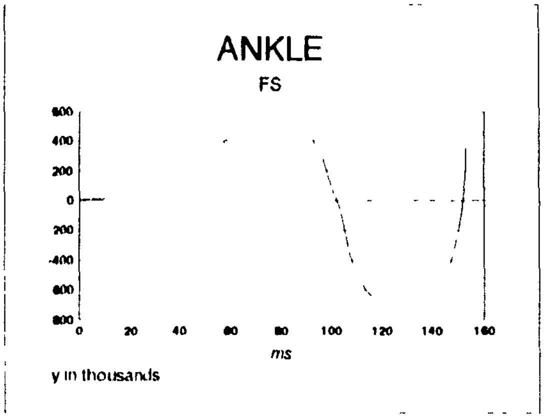
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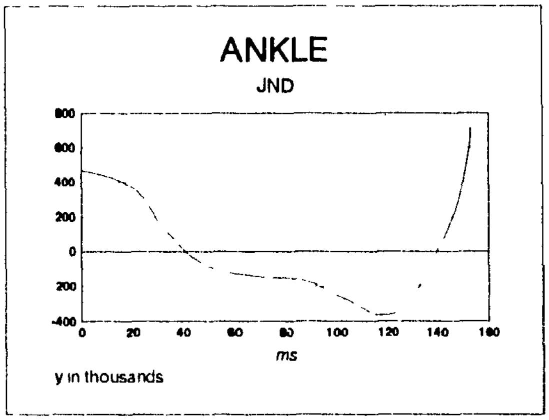
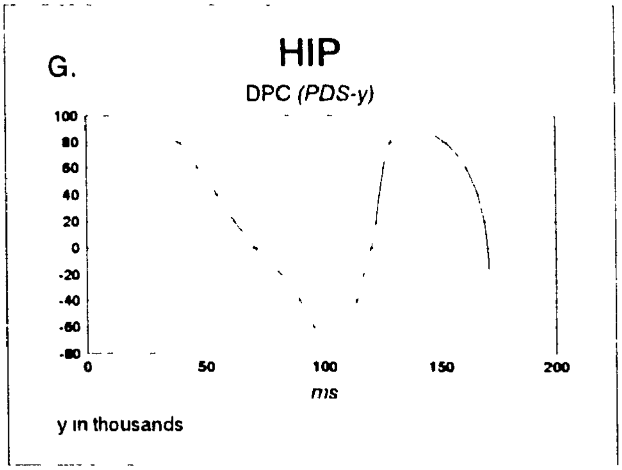
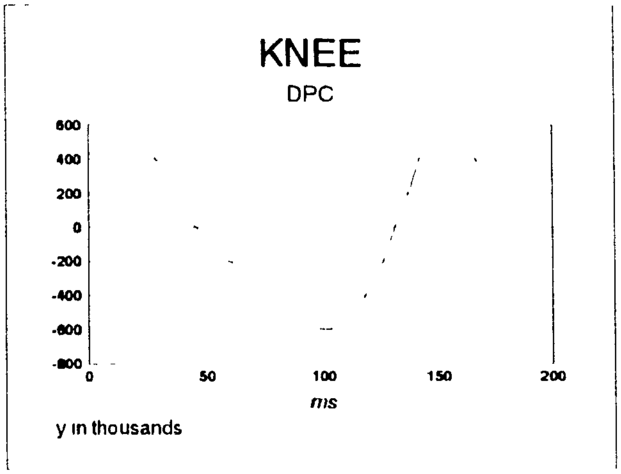
FS


ANKLE

JND

Power Time Profile





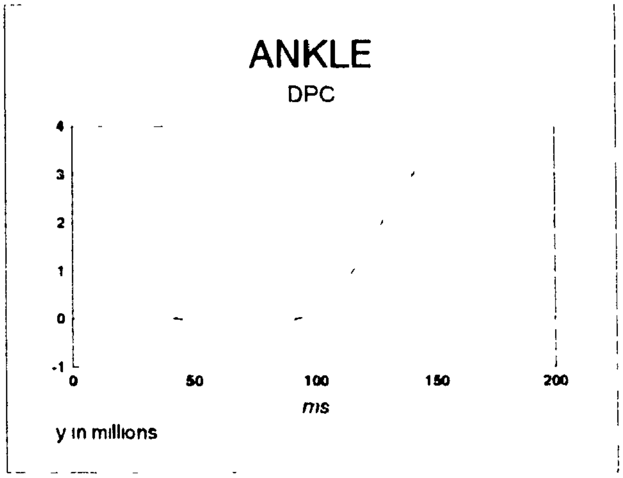


TABLE 5

A. JOINT POSITIONS POST-LANDING

	ANKLE		KNEE		HIP	
	landing position	MAX Flexion	landing position	MAX Flexion	landing position	MAX Flexion
VC	131 (4)	89 (14)	151 (4)	82 (8)	143 (2)	135 (4)
LF	132 (2)	94 (7)	170 (3)	126 (11)	130 (4)	125 (7)
JV	136 (5)	94 (5)	164 (12)	104 (12)	104 (4)	80 (13)
MPC	147 (5)	103 (3)	175 (5)	121 (6)	108 (7)	87 (9)
DPC	139 (4)	94 (6)	160 (5)	103 (9)	118 (5)	107 (7)
FS	146 (5)	107 (8)	173 (8)	119 (11)	132 (9)	113 (14)
JND	147 (4)	99 (4)	174 (4)	129 (8)	119 (7)	108 (9)
MR	124 (8)	91 (5)	138 (10)	89 (6)	124 (6)	111 (12)
FB	127 (13)	93 (3)	160 (4)	121 (7)	120 (9)	115 (9)

B. RANGE OF MOTION TO MAXIMUM FLEXION

	ANKLE	KNEE	HIP
VC	43	70	8
LF	38	44	5
JV	42	60	24
MPC	44	51	21
DPC	45	57	11
FS	39	54	19
JND	48	45	11
MR	33	49	13
FB	34	39	5

position tended to the maximum extension limit in two individuals, FS (173°) and JND (174°), while DPC adopted a more flexed knee position for landing (160°) Interestingly, at the ankle joint, a position of maximum PF was observed for all three individuals, position values ranging from 139° (DPC) to 147° (JND). The landing joint positions were distinctively different in the two older PDS individuals, particularly at the ankle The hip position was comparable to the younger PDS group with a moderately flexed position (120° for FB and 124° for MR) coupled with a moderate flexion position at the knee (138° MR and 160° FB). However, the ankle placement was at a minimum of plantarflexion with a position of 127° for FB and 124° for MR

The angle positions at landing across the three EMG classification groups can be summarized as follows: 1) The AS individual adopted a position of extension at the hip, coupled with slight flexion at the knee and PF at the ankle; 2) The TS group typically adopted a position of flexion at the hip, coupled with extension tending to the biomechanical limit at the knee and PF at the ankle; 3) The younger PDS group adopted a flexed position at the hip, associated with extension to the biomechanical limit at the knee, as well as a limit PF position; and 4) The older PDS group adopted a flexed position at the hip, with slight flexion at the knee, and a position of PF at the ankle

The standard deviation values for landing position (Table 5a) indicate a high consistency in the joint positions at landing across trials for all individuals Typically, the variation in angle position was below 10° for all joints, the highest standard deviation values noted for one individual (FB) in the older PDS group, with variability values of 13° for the ankle and 9° for the hip. Also, the classification of the trials according to the pattern of movement organization during flight failed to reveal a significant association between the movement organization during flight and the joint position at landing.

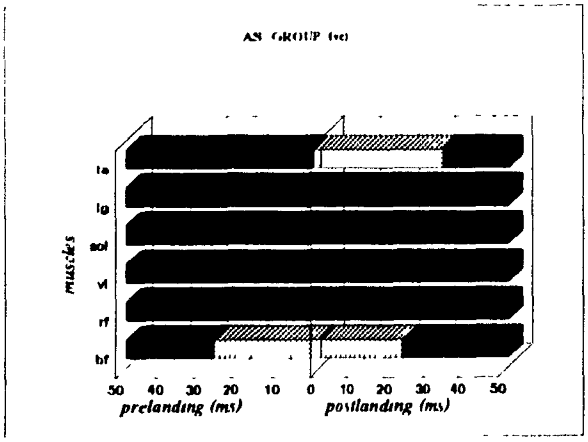
4.8 Landing:

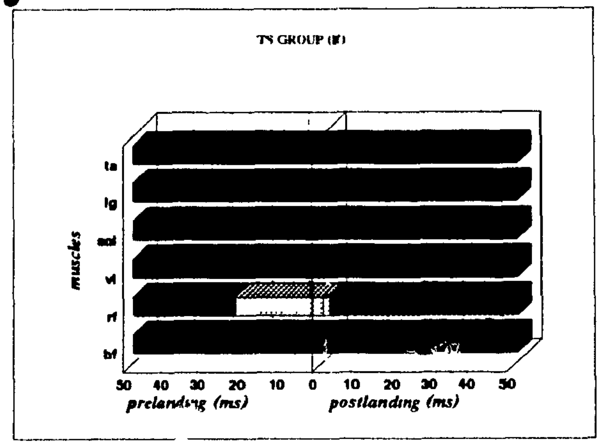
The functional consequences of the distinct movement organization patterns identified on the landing phase were defined in terms of the following parameters: 1) the modulation of the muscle activity during the impact phase; 2) the postlanding range of motion and angular velocity profiles of the hip, knee, and ankle joints; 3) the peak vertical acceleration experienced at the center of gravity at impact; and 4) the time to stability.

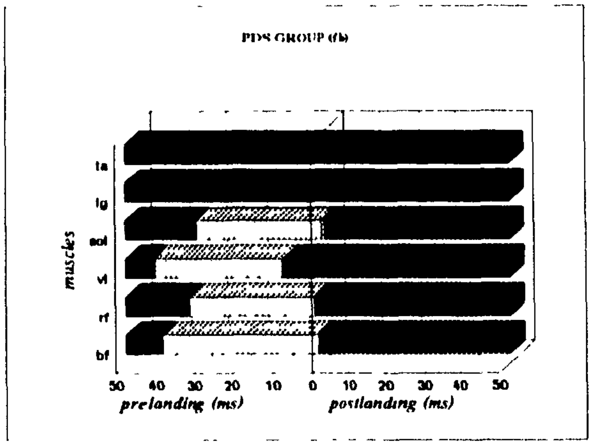
Modulation of the Landing Muscle Activity: Two distinct patterns of EMG activity were identified during the initial landing phase centering on impact: 1) a **continuous** EMG pattern which was characterized by uninterrupted muscle activity through the impact phase of landing; and 2) a **discontinuous** EMG pattern which was characterized by the presence of a period of quiescence in muscle activity during the impact phase of landing. These two patterns of landing activity for all muscles are illustrated in Figure (15) for one representative jump for each subject. Prelanding activity is illustrated to the left of the time-zero line (touchdown), and postlanding activity is placed to the right of this line The period of prelanding muscle activity is demarcated by the solid black bars, quiescence by the light diamond shading and postlanding activity by the darker grey diamond shading. In cases where activity is continuous from pre to postlanding, activity

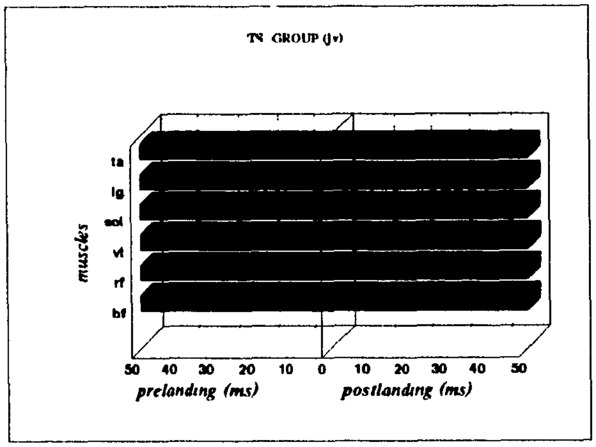
Figure 15. The EMG pattern during impact of the 6 muscles is illustrated for all individuals according to the EMG-based classification. T=0 indicates touchdown. The pattern of muscle activity is represented for the time period extending 50 ms prelanding and 50 ms postlanding. Prelanding activity (left of t=0) is indicated with solid black lines and postlanding activity (right of t=0) is indicated with darker grey diamond shading. Quiescence corresponds to the light diamond shading region. Continuous activity is designated by a solid black line throughout the interval.

EMG Activity Patterns


AS GROUP (vc)


TS GROUP (jf)


PDS GROUP (fb)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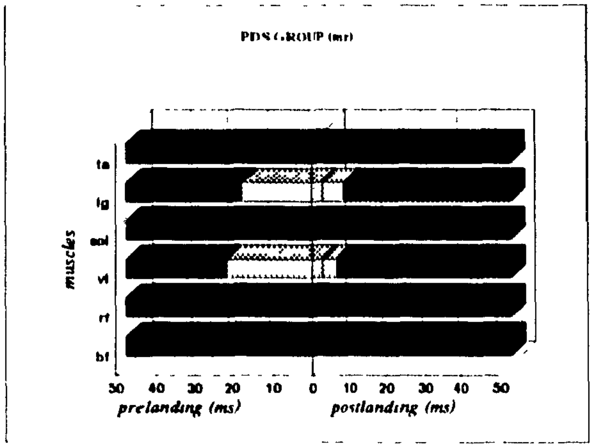
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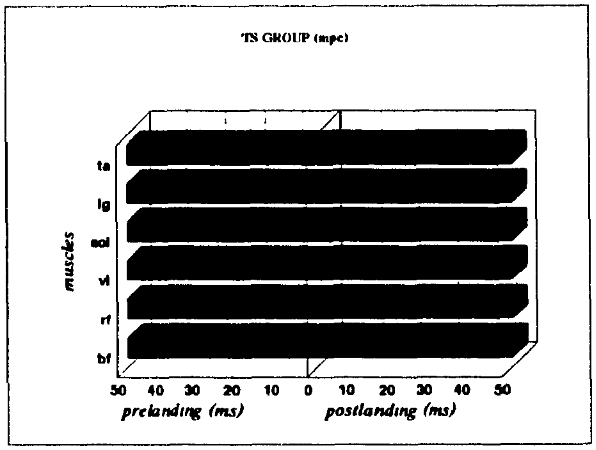
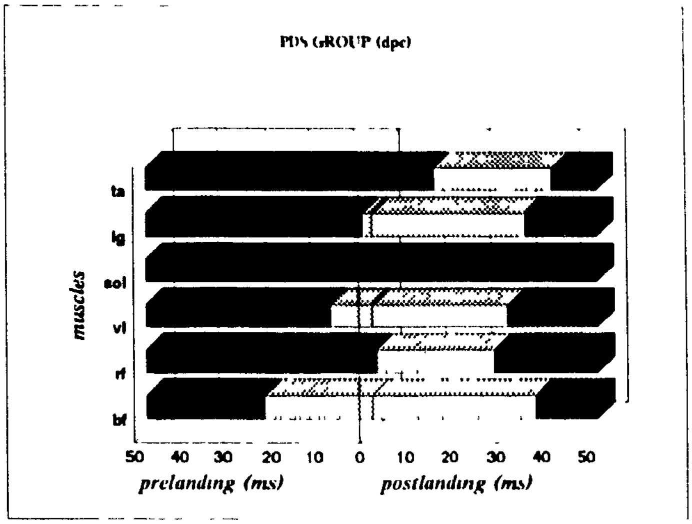
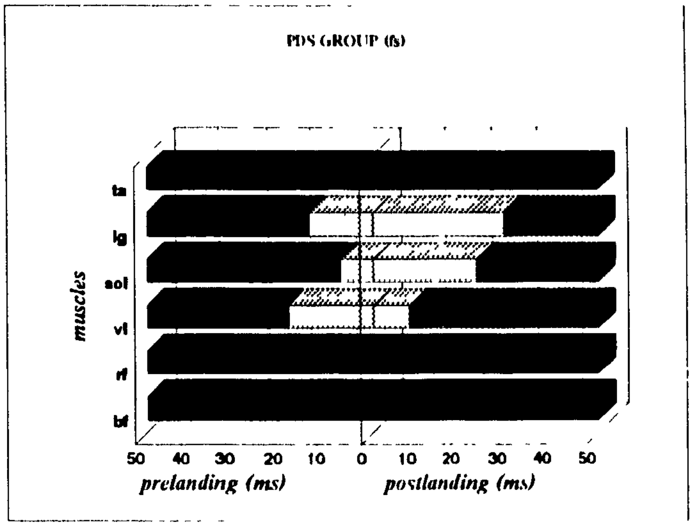
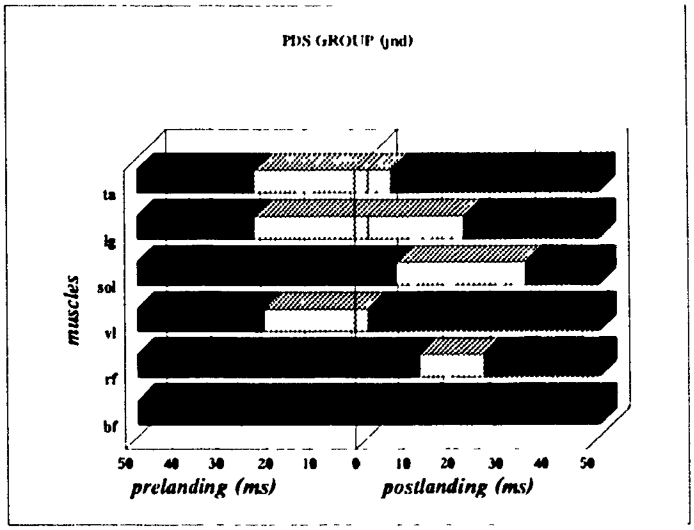

TS GROUP (mpc)


PDS GROUP (dpc)
muscles
ta
lg
sol
vl
rf
bf
50 40 30 20 10 0 10 20 30 40 50
prelanding (ms)
postlanding (ms)


PDS GROUP (fs)
muscles
ta
lg
sol
vl
rf
bf
50 40 30 20 10 0 10 20 30 40 50
prelanding (ms)
postlanding (ms)


PDS GROUP (jnd)
muscles
ta
lg
sol
vl
rf
bf
50 40 30 20 10 0 10 20 30 40 50
prelanding (ms)
postlanding (ms)

is represented by a solid black bar throughout the interval. In some cases, muscle quiescence occurred for a period both pre and postlanding (VC, the BF muscle). In other cases, it occurred either during the prelanding (FB, the RF muscle) or postlanding period (DPC, the TA and RF muscles) exclusively. Regardless of when the pattern of quiescence was observed, however, it was always centered about landing.

The pattern of muscle activity observed during the impact phase of the jump further differentiated the three EMG classification groups.The discontinuous pattern was dominant in the three younger PDS individuals, while it was virtually absent in the TS group individuals and observed in only two muscles for the AS individual. The frequency distribution for the two muscle activity patterns at impact is illustrated across the three EMG classification groups in Figure (16).

In the AS individual, the continuous pattern was dominant except in the TA and BF muscles where the discontinuous pattern was observed on 63% and 75% of trials respectively In the TS group, the discontinuous muscle activity pattern was of significance in only one individual (LF) for one muscle, the RF (57% of trials). With the exception of this muscle in this one individual, the continuous pattern of muscle activity dominated, particularly in the distal muscles where it was exclusively observed as follows: in the SOL for LF, in the TA, LG, and SOL for JV, and in the LG for MPC. In contrast, the discontinuous pattern of muscle activity was predominant in the younger PDS individuals. For the individual DPC, the discontinuous pattern was exclusively observed in the proximal muscles VL and RF, as well as being of significance in the distal muscles TA (50% of trials) and LG (75% of trials), and in the proximal muscle

BF (50% of trials). Similarly, for the individual JND, the discontinuous pattern again dominated in five of the six muscles TA (60%), LG (100%), SOL (70%), VL (80%), and RF (90%). For the remaining individual in this group (FS), the discontinuous pattern was significant in only three muscles, the LG (70%), the SOL (60%), and the VL (70%) Again, the two older PDS individuals, FB and MR, differed from their younger cohorts 1) MR tended to adopt the discontinuous and continuous patterns equally for the LG (56%) and VL (56%) muscles, while the continuous pattern dominated for the other muscles; and 2) FB adopted the discontinuous and continuous patterns with approximate frequency for the SOL (55%), VL (55%), RF (55%), and BF (55%) muscles, with the continuous pattern dominating distally in the TA and LG muscles The trial sequence again indicates that the type of muscle activation pattern during impact was not associated with the movement organization pattern during flight for all individuals

It is probable that the two patterns of muscle activity would differentially influence the stiffness characteristics of the lower extremity joints during the landing phase. The compliance of the joint complex is responsible for counteracting the passive and reactive forces induced during impact to prevent collapse Indeed, different postlanding strategies for achieving stability were observed and are presented in the following sections.

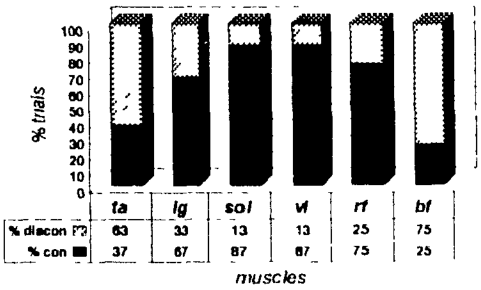
Range of Postlanding Flexion: The postlanding range of flexion was measured from the position at initial impact to the position of maximum flexion at each of the three lower extremity joints (Table 5b). The position of maximum flexion reflects the point at

Figure 16. In these frequency distributions, the 6 muscles are represented horizontally and the percent number of trials for each EMG pattern vertically. Solid bars represent the frequency (% of trials) for the continuous EMG pattern and 'hatched' bars the frequency of the discontinuous EMG pattern. Subjects are categorized according to the EMG classification.

Frequency Distribution

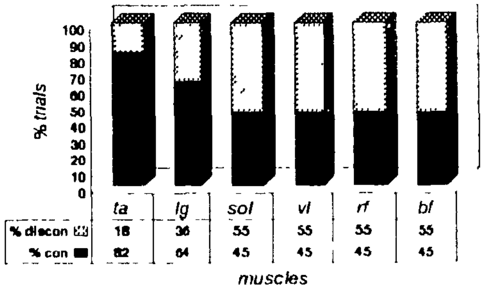
Muscle Activity Patterns at Impact

AS *(vc)*



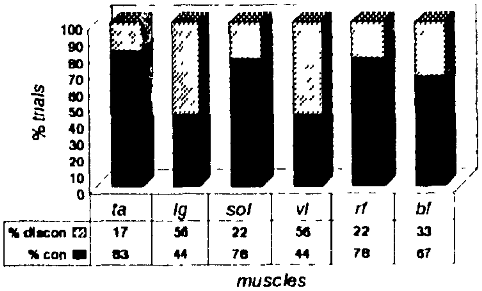
	ta	*lg*	*sol*	*vl*	*rf*	*bf*
% diacon ▨	63	33	13	13	25	75
% con ■	37	67	87	87	75	25

PDS-o *(fb)*



	ta	*lg*	*sol*	*vl*	*rf*	*bf*
% diacon ▨	18	36	55	55	55	55
% con ■	82	64	45	45	45	45

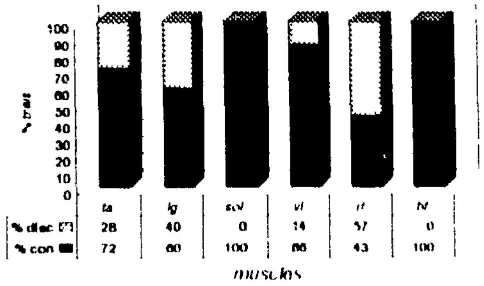
PDS-o *(mr)*



	ta	*lg*	*sol*	*vl*	*rf*	*bf*
% diacon ▨	17	56	22	56	22	33
% con ■	83	44	78	44	78	67

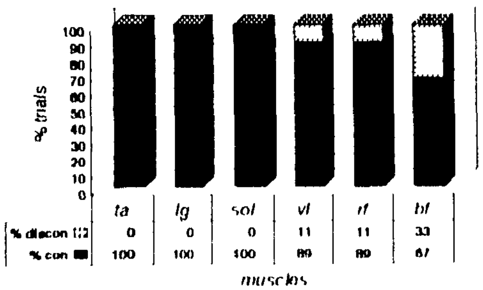
Muscle Activity Patterns at Landing

TS *(ll)*



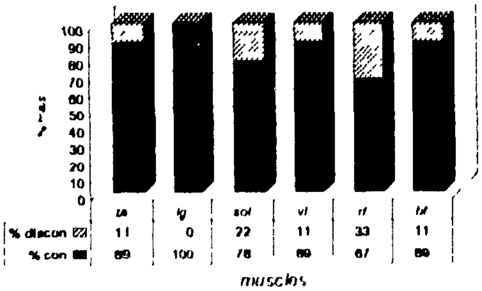
	ta	*lg*	*sol*	*vl*	*rf*	*bf*
% diac ▨	28	40	0	14	57	0
% con ■	72	60	100	86	43	100

TS *(jv)*



	ta	*lg*	*sol*	*vl*	*rf*	*bf*
% diacon ▨	0	0	0	11	11	33
% con ■	100	100	100	89	89	67

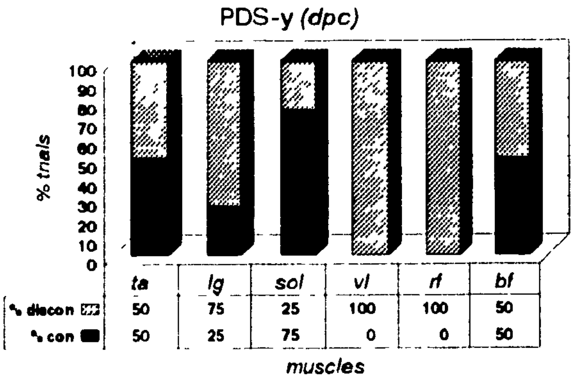
TS *(mpc)*



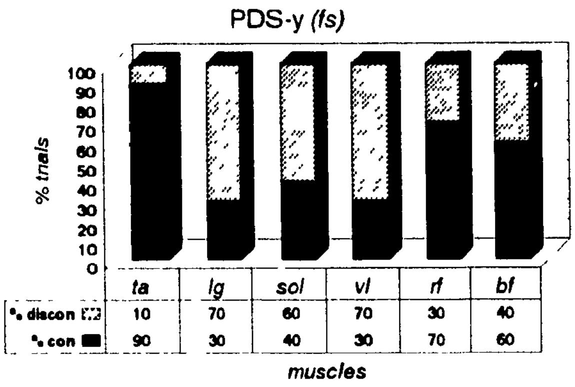
	ta	*lg*	*sol*	*vl*	*rf*	*bf*
% diacon ▨	11	0	22	11	33	11
% con ■	89	100	78	89	67	89

Frequency Distribution

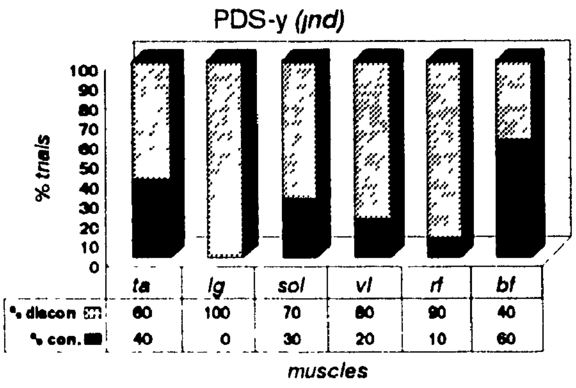
Muscle Activity at Landing


PDS-y *(dpc)*

	ta	lg	sol	vl	rf	bf
% discon ▨	50	75	25	100	100	50
% con ■	50	25	75	0	0	50


PDS-y *(fs)*

	ta	lg	sol	vl	rf	bf
% discon ▨	10	70	60	70	30	40
% con ■	90	30	40	30	70	60


PDS-y *(jnd)*

	ta	lg	sol	vl	rf	bf
% discon ▨	60	100	70	80	90	40
% con. ■	40	0	30	20	10	60

which the impact forces (including gravity) have been effectively counteracted and the extension motion to regain upright posture can be initiated.

For the AS individual, the postlanding flexion motion was primarily absorbed at the knee (70°, $p < .01$) and ankle joints (43°), with only a small amount of flexion experienced at the hip joint (8°). This sequence of joint flexion absorption was also observed for the individuals in the TS and PDS groups, such that the major flexion ROM was located at the knee and the hip experienced the least amount of flexion. However, a different partitioning of the total flexion motion among the lower extremity joints was observed across the three classification groups to yield distinct postlanding profiles. The TS individuals manifested a decrease in flexion range at the knee such that ROM at the two distal joints was more equal: 44° to 60° for the knee and 38° to 42° at the ankle joint. The amount of hip flexion motion was individually specified, flexion values ranging from a minimum 5° for LF to a maximum 24° for JV. In the younger PDS individuals, comparable flexion ranges are experienced at the knee (45° to 57°) and ankle joints (39° to 48°). Again, a minimum amount of flexion was observed at the hip (11° to 19°). The older PDS subjects, MR and FB presented a profile closer to that of the TS subjects in that hip and knee flexion was moderate and evenly distributed. Hip motion for MR was within the range of the other PDS subjects (13°) while for FB, range of motion was similar to that of the AS subject (5°).

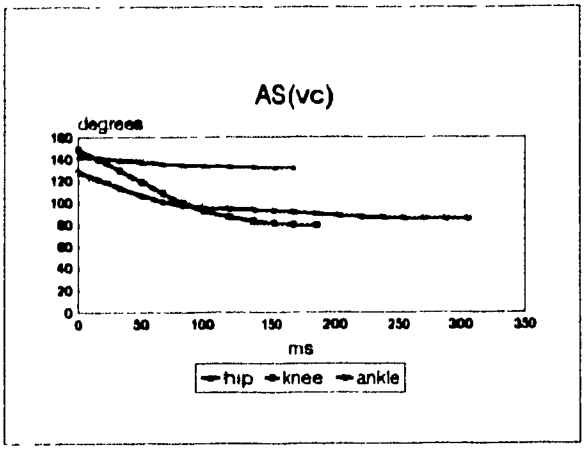
The postlanding flexion profiles could also be differentiated by the variability in the maximum flexion positions across trials. This position variability is represented by the standard deviation limits in Table (5).

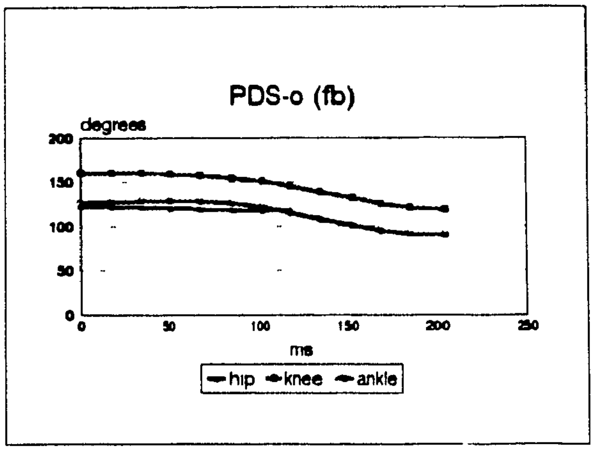
For the AS individual, the maximum flexion positions were consistent for the ankle and hip joints (sd = 4°), while the position variability was slightly higher at the knee joint (sd = 8°). A similar proportion of position variability was observed for the TS group individual LF: sd = 7° for the ankle and hip, and 11° for the knee. In contrast to these two individuals, the remaining TS and PDS individuals showed higher variability in end flexion position at both the knee and hip joints, the variability remaining low at the ankle This may indicate an increased contribution of the hip joint in the absorption of the landing forces in these individuals.

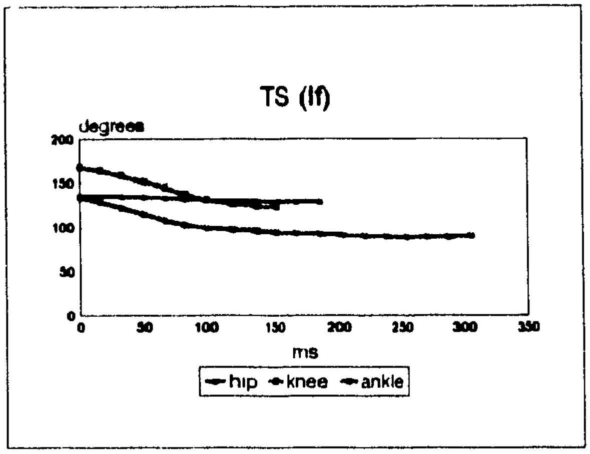
Sequence of Postlanding Joint Flexion: The time period over which the postlanding flexion phase was distributed across the three joints is illustrated in Figure (17). The graphs represent the mean movement duration from impact to the point of maximum flexion for the representative individuals in each of the three EMG classification groups. The salient contrasting points across the three groups are as follows: 1) For the AS profile, the duration of the flexion movement was significantly longer at the ankle joint ($p < .01$). The flexion duration at the hip and knee joints were comparable, typically terminating within the first 200 ms postlanding; 2) A similar profile was observed for the TS group, the duration of the flexion movement being significantly longer at the ankle joint ($p < .01$), with comparable duration values noted for the hip and knee; 3) In the younger PDS group, the duration was comparable at all three joints. Also, the maximum flexion position was reached within 200 ms postlanding at all three joints; and 4) The two older PDS individuals presented different flexion profiles. For FB, the flexion duration

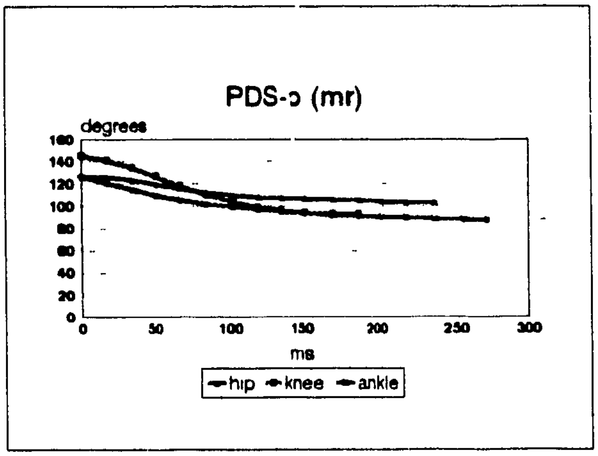
Figure 17. The time distribution of the postlanding flexion range is illustrated for one representative individual in the AS, TS, and PDS(y) groups, and for the two individuals in the PDS(o) group. T=0 indicates landing, and the postlanding period (ms) to maximum flexion at the hip, knee, and ankle joints is represented along the abscissa. The joint positions are represented along the ordinate.

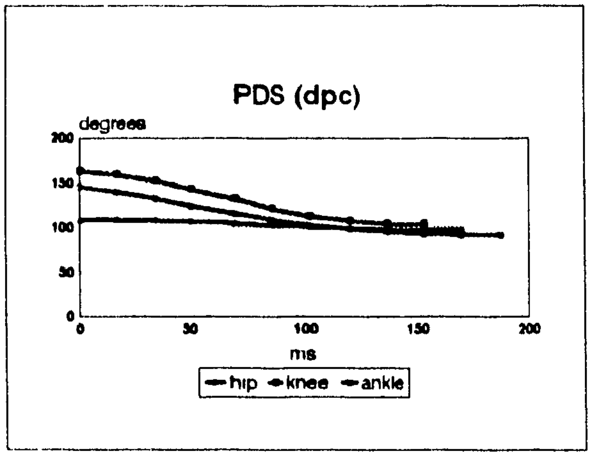
Postlanding Flexion Distribution


AS(vc)


PDS-o (fb)


TS (lf)


PDS-o (mr)


PDS (dpc)

was longer at the ankle and knee joints ($p < .01$), with a rapid application of the flexion movement at the hip joint. Again, the maximum flexion position was attained within 200 ms at all three joints. Conversely for MR, slightly longer durations were noted at the hip and ankle joints as compared to the knee ($p < .05$).

4.9 Postlanding Stability Profiles:

Due to the absence of force data at landing, postlanding stability was defined in the kinematic domain rather than in the dynamic domain. Postlanding stability was defined as the point at which the reactive forces generated at impact are equilibrated and consequently, the induced oscillations at the center of gravity are reduced to a minimum. Using kinematic variables, this point of stability was defined as the time at which the vertical and horizontal linear velocity components at the iliac crest oscillate around a minimum displacement line Three distinct patterns of postlanding stability were observed and could be related to the type of muscle activation pattern centered around landing. These profiles are illustrated in Figure (18) with the associated vertical acceleration impulse at the iliac crest experienced during the initial phase of landing for the representative subjects.

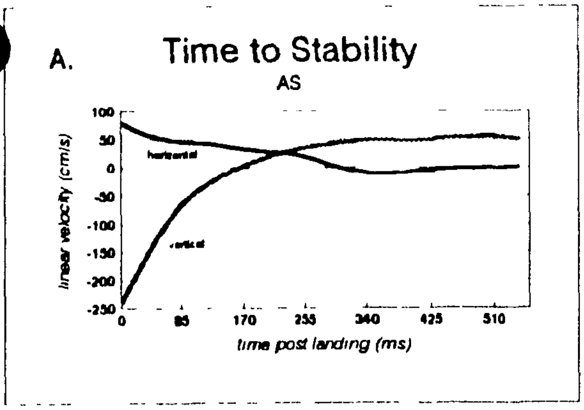
In the AS individual, the discontinuous EMG pattern in the TA and BF muscles would limit coactivation at all three joints during impact The associated stability profile was characterized by a uniform decrease in both the vertical and horizontal velocity components from the time of landing to the point of stabilization A peak postlanding vertical acceleration value of (3866 cm/sec/sec) was noted with this stability pattern.

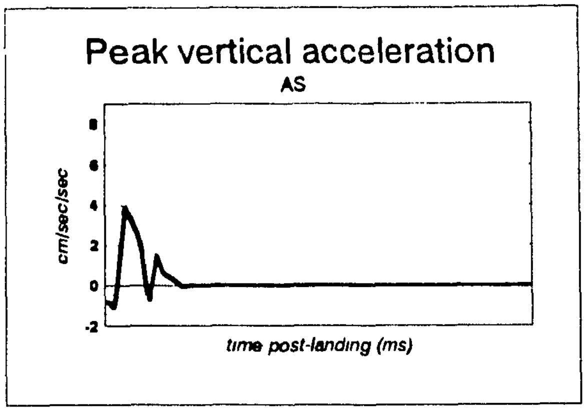
Proximal and distal coactivation were similarly limited in the younger PDS individuals (DPC, FS, and JND) In the representative trial illustrated in Figure (15), EMG quiescence during impact was present in two distal muscles (TA and LG) and three proximal muscles (VL, RF, and BF). The associated stabilization profile was characterized by an initial overshoot in the compensation of the vertical velocity component with a subsequent uniform decrease in the amplitude of both linear velocity components to stability A peak vertical acceleration value of (3361 cm/sec/sec) was noted with this profile, and was similar to the acceleration value for the AS individual. In contrast to the AS and PDS groups, the continuous EMG pattern was dominant in all muscles during impact for the TS group individuals. Consequently, a coactivation at all three joints was present during the impact phase. This coactivation pattern was associated with an initial sharp decrease in the vertical linear velocity, as well as with a significant overshoot in the initial vertical compensation and a series of oscillation to stability. A higher peak vertical acceleration value of 6128 cm/sec/sec was observed with this stability profile.

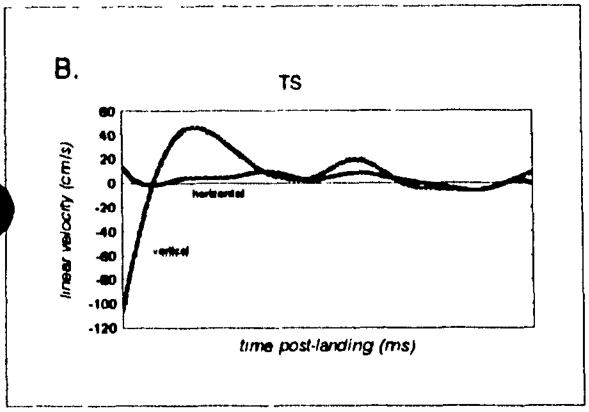
Again, distinct differences in the stabilization profiles were noted for the two older PDS individuals, FB and MR For the subject FB, the period of quiescence was early in the SOL such that a continuous activity was found for this muscle through landing. Conversely, the quiescent period was initiated only postlanding in the LG muscle, while a continuous activity was observed in the TA. Consequent to this distal pattern of activation at landing, there was coactivation at the ankle during impact. Proximally, the period of quiescence in the VL terminated prior to landing while being present in the RF and BF muscles at landing, eliminating coativation at the proximal joints. The distal coactivation pattern in this individual was associated with a stabilization profile which was similar to that of the TS group: an initial overshoot in the vertical compensation, followed by an oscillatory damping of the vertical linear velocity to landing. The peak acceleration value at landing was similar to the AS value at 4274 cm/sec/sec. However, the second reactive peak in vertical acceleration was less damped, with a value of 1208 cm/sec/sec. For the subject MR, the quiescent periods were appropriately timed in the ankle muscle LG and the knee muscle VL. However, as a continuous pattern was observed for the remaining muscles, coactivation was present at all three joints during the impact phase. The stability profile was similar to that of the AS individual: a uniform decrease in the horizontal and vertical linear velocity components to stability. However, the initial deceleration phase was prolonged, a longer period being required to compensate for the vertical impact forces at landing. The peak acceleration value at the iliac crest of 6178 cm/sec/sec was comparable to the TS group.

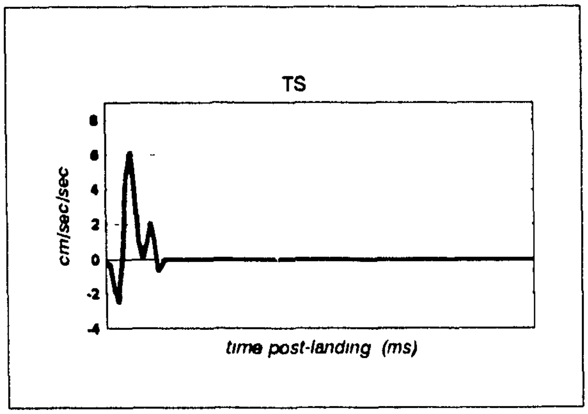
Time to Stability: The last feature of the jump-down to be investigated in this study was the time to stability associated with the distinct movement organizations across the three classification groups. Time to stability refers to the time at which the horizontal and vertical linear velocity signals begin to oscillate about a minimum value. The time to stability for all individuals is illustrated in Table (6). The two oldest children, VC and MR, displayed the longest time to stability with values of 233 ms and 327 ms respectively. Interestingly, these same individuals displayed the smoothest stability profiles, with an absence of overshoot of the initial peak vertical acceleration impulse. However, the time to stability was significantly more variable for MR, with a standard deviation value of 70 ms as compared to 35 ms for VC. The minimum time to stability was noted for the remaining older PDS individual FB, with a mean value of 134 ms and variability of 17 ms. The time to stability and variability values were comparable for the TS and younger PDS individuals, mean values ranging from 145 ms (JND) to 184 ms (JV) and variability values ranging from 18ms (MPC) to 47 ms (JV).

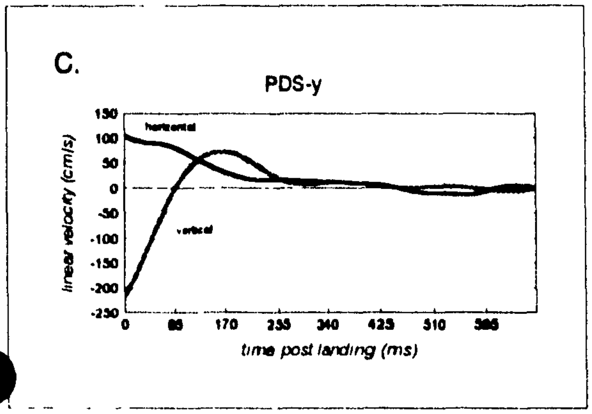
Figure 18. The stability profiles and peak vertical acceleration (iliac crest) at impact are illustrated for the representative individual in the 3 classification groups (AS, TS, and PDS(y)) and the PDS(o) individuals. T = 0 indicates touchdown. The vertical (light grey) and horizontal (dark grey) linear velocity component at the iliac crest are represented from T=0 to the point of stability (minimum oscillations). The corresponding peak vertical acceleration profiles are illustrated to the right of each stability profile.

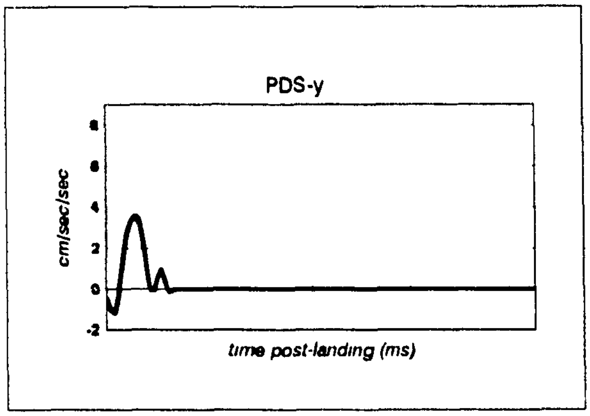

A.
Time to Stability
AS
100
50
0
-50
-100
-150
-200
-250
linear velocity (cm/s)
horizontal
vertical
0
85
170
255
340
425
510
time post landing (ms)

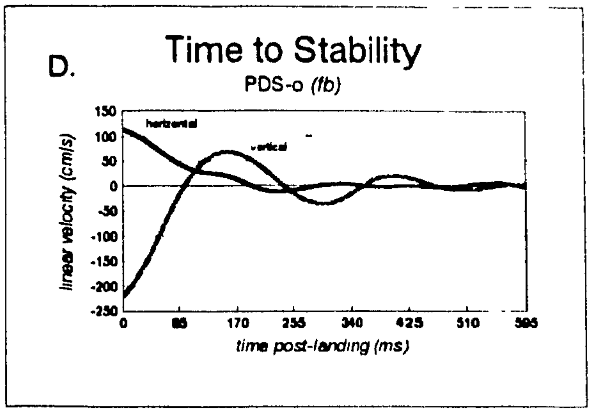

Peak vertical acceleration
AS
8
6
4
2
0
-2
cm/sec/sec
time post-landing (ms)


B.
TS
60
40
20
0
-20
-40
-60
-80
-100
-120
linear velocity (cm/s)
horizontal
vertical
time post-landing (ms)


TS
8
6
4
2
0
-2
-4
cm/sec/sec
time post-landing (ms)


C.
PDS-y
150
100
50
0
-50
-100
-150
-200
-250
linear velocity (cm/s)
horizontal
vertical
0
85
170
255
340
425
510
595
time post landing (ms)

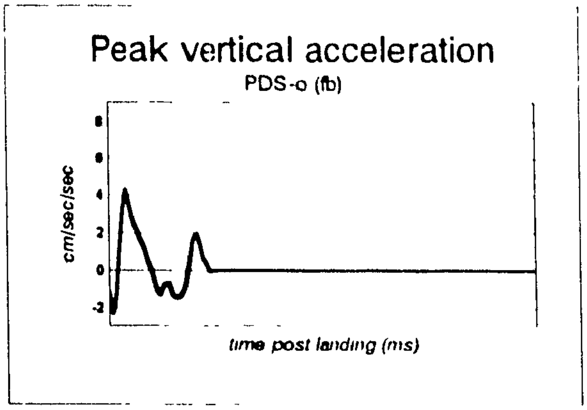

PDS-y
8
6
4
2
0
-2
cm/sec/sec
time post-landing (ms)



D.

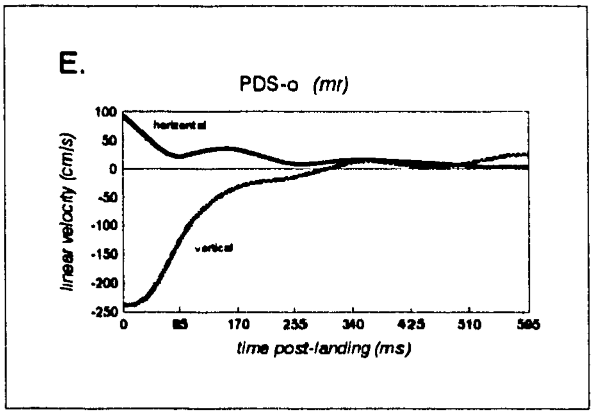
Time to Stability

PDS-o *(fb)*



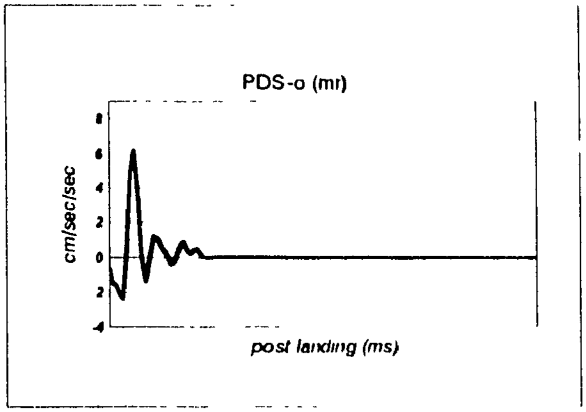
Peak vertical acceleration

PDS-o (fb)



E.

PDS-o *(mr)*



PDS-o (mr)

TABLE 6

TIME TO STABILITY (ms)

PDS (young)	DPC	154.87	(128.39)
	FS	180.71	(135.39)
	JND	144.5	(15.81)
PDS (old)	FB	134.3	(16.8)
	MR	326.74	(70.06)
TS	LF	155.74	(22.44)
	JV	183.94	(46.75)
	MPC	153	(17.85)
AS	VC	233.26	(34.85)

CHAPTER FIVE: DISCUSSION

Research in human development (Forssberg and Nashner, 1982, Woollacott, 1988) has suggested that the sensorimotor capacity required for the generation of adult movement profiles evolves during the critical ages of 7 to 9 years The focus of this study was to define an analysis approach which would identify the joint and muscle parameters closely related to the emergence of the adult capacity for the task of landing from a jump-down. The term 'strategy' is used in this study to denote distinct muscle and joint landing patterns. This definition does not imply the following. 1) the existence of a finite number of landing patterns; 2) a 'fixed' and unmodifiable nature for these landing patterns; or 3) a cognitive aspect in the selection of one pattern over the others Strategy simply refers to the stable complement of muscle onset and interference patterns, and the associated joint coordination patterns which individuals adopt to execute the landing task.

Landing from a jump-down was selected to investigate these emerging control principles as it is an unconstrained motor behaviour found within the natural repertoire of a child's play pattern. The study of natural movements avoids interpretations that could be confounded by differences in a child's ability to learn a new task or to adapt to unnatural constraints and expectations. The only constraint in our paradigm was the contribution of the upper extremity to the control of landing. As the maximum variability was maintained, any consistent trends in the movement profile could be more closely attributed to developmental differences.

5.1 EMG Classification.

The central core of this study was the definition of a classification scheme representing the progression from a proximal-distal to a distal-proximal muscle organization of the landing pattern. The progression was defined by three distinct muscle activation patterns: the PDS, the TS, and the AS patterns. The progression was also correlated to an increasing capacity to simultaneously modulate activity in both anterior and posterior muscle compartments. For example, in the PDS group, activity was initiated in the proximal and distal anterior compartment muscles, with activity in the posterior compartment muscles restricted to the final and postlanding phases. In contrast, a coincident activation in both muscle compartments was observed in the TS and AS patterns. Another differentiating feature was the lack of consistency in the TS group to adopt one dominant muscle pattern as compared to the AS and PDS groups. The lack of consistency in the pattern of muscle landing activity could reflect, as the name suggests, a 'transitional' stage in which there is difficulty in establishing the reliability of a muscle pattern to meet both external and internal conditions. This variability may represent an 'exploration' of the reliability of control parameters as the child moves from one stable pattern (PDS) to the next (AS). The three EMG landing patterns may therefore represent the organization of the muscle activity which preferentially optimizes the child's stability requirements during a particular stage of growth and development, rather than suggesting that one muscle activation is more 'developmentally' advanced than another.

Validity of Classification: The question then arises as to whether the classification scheme based on EMG activation patterns is a valid descriptor of landing skill acquisition across the developmental period investigated in this study. The performance of each group of individuals demonstrated distinctly identifiable characteristics in the kinematic profiles that could be matched to the predominant EMG activation pattern The strongest kinematic correlate to the EMG classification scheme was found to be the variability profile, specifically during the final phase of flight, for which distinct profiles idiosyncratic to each classification group were noted

5.2 Functional Consequences of the Landing Muscle Patterns and Related Kinematic Parameters to the Control of Landing:

The following discussion attempts to provide a framework in which the emerging organizational principles identified in the study would be accommodated. The focus is on the contribution of the distinct movement organization for the three EMG classification groups to the impact phase of the jump.

Movement organization during flight: Kinematically, movement at one joint of a segment will induce an equal but opposite torque at the other joint of a segment. In an optimal system, an extensor torque at the hip would induce an extensor torque at the knee and a plantarflexion torque at the ankle, while hip flexion would induce a flexion torque at the knee and a dorsiflexion torque at the ankle. The *In-phase* and the *Out-of-phase* joint coordination patterns and their organization into a movement pattern of the limb during flight could reflect different adaptations of the transfer of passive forces in anticipation of landing. The coupling of the movement direction in the *In-phase* pattern would be optimal for the proximal-distal transfer of passive forces while the dichotomous motion of the *Out-of-phase* pattern would mechanically limit such a transfer of passive forces.

In the AS profile, the proximal *In-phase* pattern would support the transfer of passive forces from the hip to the knee. The coupling of the direction of motion at the two joints would also maintain consistent length-tension properties of the RF and BF muscles which may contribute to the transfer of passive energy. The dichotomous organization at the distal segment would limit the further transfer of passive forces to the ankle joint. This is important, as ankle position is critical for the adaptive behavior of the landing pattern (McKinley and Pedotti, 1992). The early distal muscle coactivation would further contribute to limit the influence of the motion-dependent torques on the ankle to a minimum. The tonic activity in the plantarflexor muscles through both the PF and DF phases of ankle motion would support the contribution of this activity to stabilizing the ankle position. The lengthening force applied to the LG and SOL muscles could also contribute to the modulation of the stiffness properties at the ankle joint which would optimize the absorption of impact forces (Alexander and Vernon, 1975).

The biomechanical outcome of the movement organization in the TS and younger PDS individuals is in clear contrast to the AS profile. At the proximal segment, the *Phase-lag* and *Freezing* patterns were often introduced. In the *Phase-lag* pattern, the joint reversal at the knee always preceded reversal at the hip joint and could arise from anthropometric differences. The length and weight of the thigh segment in the younger individuals were less than in the AS individual, such that a given muscular force applied at the hip joint would generate a comparatively greater angular velocity at the thigh segment. If this anthropometric parameter factors into the movement organization, then the knee would reach end-range positions more rapidly than the hip, yielding the observed pattern of the leading joint reversal at the knee. Early proximal muscle coactivation may be required as a 'braking' mechanism against the induced motion-dependent torques at the thigh segment. In corroboration with this hypothesis was the finding that the oldest PDS individual (MR) did not display the *Phase-lag* or *Freezing* patterns. In fact, this individual, whose height and weight parameters were similar to the AS individual, manifested a similar coincident proximal *In-phase* strategy. The Freezing pattern can therefore be considered as a 'limit' strategy used to constrain the passive forces at the knee induced by hip motion. Applied muscle work would limit the passive forces by preventing hip motion. Thelen (1991) has reported the utilization of proximal stabilization techniques by young children to generate goal-directed reaching movements which display little variability in the hand trajectory. The positive work required to stabilize the hip joint would significantly contribute to the positive power-time hip profile noted during the final phase of flight.

The movement organization was also different at the distal segment. Both the *In-phase* and the *Out-of-phase* patterns were associated with coactivation in the TS individuals, while for the PDS(y) group, anticipatory activity was noted in the TA and SOL muscles, LG activity being restricted to the postlanding phase. These activity patterns were associated with PF positions at landing, tending to the biomechanical limit in both groups. Interestingly, the anticipatory activity in the LG was associated with negative power-time profiles at the ankle in the TS, while the absence of LG activity in the PDS(y) was associated to power production rather than absorption at impact. Therefore, despite the more plantarflexed position and the selection of either the *In-phase* or *Out-of-phase* coordination pattern across the TS group when compared to the AS profile, the distal absorption profile was beginning to emerge in these individuals.

Thus, it would appear that the movement patterns in the younger individuals are organized to constrain the influence of motion-dependent torques to assure stability while the movement organization adopted by the AS individual would seem to optimize these forces. This optimization of passive forces could be used to optimize a performance index, such as the total amount of work (Pedotti et al; 1989).

The central tendency positions, the operation range, and the limit position of the operational range were found to be sensitive indexes of the EMG classification groups. The significance of these operating range features may be better evaluated in relation to management of entire limb workspace in generating a movement. This aspect will be addressed in further research.

Freezing of Degrees of Motion: To 'set' the joint configuration for landing, the position degrees of freedom must be progressively constrained during flight. The laws of mechanics are such that the lost freedoms of position will be converted into freedoms of force and torque (Hollerbach, 1985). Therefore, the sequence and timing of the final joint reversals will dictate the adaptive capacity of the landing pattern. In the AS profile, joint reversals at all three joints occurred during the final phase of flight. This late timing would allow a possible re-evaluation of all preconditions prior to 'setting' the anticipatory behaviour. Although the joint reversals were considered to be coincident, due to overlapping variance, the distal-proximal sequence is preserved in the mean joint reversal pattern which would allow the 'freed' freedoms of force and torque to be applied to the trunk. Also, as the hip was the last joint to reverse, the multiple degrees of freedom at the trunk could be accessed for landing adaptability. This adaptive role of the hip joint could explain the increased variability in the timing of reversal at this joint

In contrast, in the TS and younger PDS movement organization, final landing positions at the proximal joints were initiated early during flight, particularly for the hip joint where a 'freezing' was often observed. The freezing of the hip would create a rigid coupling between the trunk and lower extremity. This functional linking could limit the movement of the body around the center of gravity, thereby stabilizing the position of the center of gravity in relation to the anticipated base of support. Similar functional couplings of the trunk have been reported in the initial learning of whole body tasks, such as learning to use a ski slide (Vereijken et al., 1992). However, certain consequences of this proximal stabilization should be noted: 1) The degrees of freedom at the trunk could not contribute to landing adaptations; 2) Freezing of the hip position would automatically reduce the available workspace at the limb, which in turn would limit the cartesian area in which the foot can land. Again, this would reduce the adaptive potential to address unanticipated conditions at landing; and 3) The number of degrees of position freedom are progressively transfered distally and are finally constrained by the biomechanical limits of the ankle. The maximum PF position may assure this biomechanical constraint, but may also be a predisposition to injury due to the limited degrees of position freedom (2°) available at the ankle joint proper. Interestingly, the variability in joint reversal time was largest at the *first* joint to reverse, suggesting that the proximal freezing of joint position may be adaptive.

Movement organizations centering on *Freezing* patterns have previously been associated with the learning stages of a task (Bernstein, 1967; Vereijken et al., 1992). Initial coordination solutions aim at freezing out and thereby reducing the number of degrees of freedom to a manageable number for the task to be performed. These degrees of freedom are released progressively through learning to be incorporated into a dynamic and controllable system.

Landing: Two movement organizations interact during the landing phase of the jump-down: 1) An anticipatory phase which is organized during flight in relation to the magnitude of the impact ground reaction force (Mizrahi and Susak, 1982; Stacoff et al., 1988). Anticipatory muscle tensions are organized to reduce the amount of stretch applied during the initial impact phase and thereby optimize energy absorption by the passive structure of the joints (Farley et al., 1991). This anticipatory property is important when considering that some external impact forces occur within 30-50 ms of landing and therefore are applied too quickly to be appropriately addressed by a neuromuscular reaction response (Lees, 1981; Devita and Skelly, 1992); and 2) A reactive phase addresses the stabilization of posture and includes stretch-mediated reflex activity. The joint position configuration at impact will dictate the application of the reactive moment, which must be addressed to prevent collapse. The postlanding flexion profile, which determines the transfer of these forces along the musculoskeletal chain, contributes to the absorption of impact forces. The contribution of this reactive phase will be addressed in further research.

The three classification groups tend to optimize different postlanding parameters. In the AS individual, the slight PF at the ankle coupled with flexion at the knee and extension at the hip would situate the reactive moment vector anterior to the ankle joint (inducing a DF moment), posterior to the knee joint (inducing a flexion moment) and approaching the center of gravity at the hip joint. The reactive moments would therefore tend to a minimum at the center of gravity. This landing joint configuration was associated with a discontinuous EMG pattern in the TA and BF muscles The pattern of quiescence is thought to be adaptive in nature as activity in the TA and BF would enhance the collapsing forces of gravity by contributing to the application of the flexion moment at the knee. The eccentric activity in the knee extensor and ankle plantarflexor muscles at impact would contribute to energy absorption, slowing of the angular displacement of the segments, thereby providing a 'braking' mechanism. Devita and Skelly (1992) found that eccentric work in the ankle plantarflexors provided the major energy absorption function, followed by the knee and the hip extensors The mechanical energy would subsequently be degraded into heat through relaxation of the muscle (Cavanagh, 1977). In the postlanding phase, maximum flexion is experienced at the knee with a significant contribution at the ankle joint. However, the application of the flexion movement was significantly longer at the ankle. The slightly higher variability in the position of maximum flexion at the knee may reflect the adaptive role of the knee in energy absorption (Cincera and McKinley, 1993). The consistent position patterns suggests that this is a standardized landing organization. The pattern was efficient in anticipating the ground reaction forces (as indicated by the lower peak vertical acceleration values experienced at the iliac crest during impact) and in assuring postlanding stability (as indicated the smooth stabilization profiles).

In contrast, the joint positions at landing in the TS and younger PDS groups were organized to reduce the reactive forces experienced at the ankle and knee joints. This was afforded by adopting a flexed position at the hip, associated with knee extension and ankle plantarflexion positions which tended to the biomechanical limit. The reactive force vector at impact would be applied near the center of rotation for both the knee and ankle joints. Limit positions and the position of the reactive force vector near the axis of rotation were effective in limiting the impact forces experienced at the elbow in cats landing from a jump, regardless of jump height (McKinley et al., 1983). Reducing the reactive moments at the knee joint may be an adaptive strategy for a system having difficulty in accurately predicting the impact of the ground reaction force, as the reactive moment at the knee is the major contributor to the mechanical moments that muscle moments must oppose (Alexander and Vernon, 1975; McKinley and Pedotti, 1992; Cincera and McKinley, 1993). The limit position and coactivation at the distal segment in the TS group may increase the stiffness properties of the distal joints as well as facilitating postlanding stretch-mediated reflexes. These two parameters may be important in this landing organization as the flexed hip position would project the center of gravity anterior to the base of support. Consequently, any miscalculations at impact would result in a forward fall if not properly compensated. This increased stiffness is reflected in the high peak vertical acceleration at impact, the oscillations in the postlanding stability profiles possibly being induced by the mixed interaction of anticipatory and reflex activity. The pattern of quiescence in the PDS(y) group may be adaptive in decreasing some of the compressive forces contributed by coactivation The muscle quiescence could therefore reduce the joint stiffness at impact. The increase in resulting joint compliance is associated with peak vertical acceleration values and stabilization profiles comparable to the AS individual.

Interestingly, from the limit positions at both the knee and ankle, comparable ranges of postlanding flexion were experienced at both joints However, the early LG activity in the TS group was associated with a significantly longer application of the flexion range at the ankle joint while durations were comparable for the knee and ankle joints for the younger PDS individuals. This again indicates the emergence of energy absorption capacity in the TS group (negative power-time graphs at the ankle).

The Period of Muscle Quiescence: In this study, the significance of the quiescent period at landing in the AS and younger PDS individuals could only be inferred from the postlanding mechanics and therefore were addressed from a perspective of force production and force absorption. Several possible contributions of the muscle quiescence on the generation of a movement are proposed in the literature and are briefly discussed in relation to the landing task.

First, at the level of movement production, it has been suggested that muscle quiescence or pre-movement silence (PMS) facilitates the acceleration of the limb segment (Mortimer and Eisenberg, 1982; Conrad et al, 1983). The increased accelerative force must be considered in relation to the stretch-shortening cycle (Komi, 1984; Norman and Komi; 1979). However, this functional outcome of quiescence may be counterproductive for landing. The quiescence is centered around landing, a time when the foot is fixed to the ground thereby forming a closed kinetic chain system. In the AS profile, the increased acceleration subsequent to the period of quiescence in the TA and BF would increase the ankle dorsiflexion and knee flexion movements and thus enhance the collapsing forces of gravity. The younger PDS individuals further present quiescence in the extensor muscles LG and VL. Significant muscle power values would be required from these muscles to overcome the flexion forces and produce a significant extension movement at the ankle (which would further destabilize the center of gravity) and knee joints, making this function an unlikely option to be incorporated in the control of landing.

Secondly, at the joint level, the muscle quiescence would influence the compliance properties of the joint complex involved in the absorption of the impact forces. The joint stiffness parameters are provided by the inherent stiffness of the joints as well as by the intensity of muscle tonus around the joints (Takanashi, 1980). The attenuation profiles for the vertical acceleration at the center of gravity indicate that the discontinuous pattern in the AS and younger PDS individuals may contribute to reducing the initial vertical impulse in reactive force experienced at landing through a differential modulation of the limb stiffness. Thus, the results of this study would support a more favourable contribution of quiescence to the energy absorption phase of landing rather than in energy production.

At the muscular level, the period of quiescence could also be involved in the fine tuning of the mechanical properties of the muscles, particularly the viscoelastic component. Viscoelasticity is important as it acts instantaneously to resist perturbations, thereby circumventing the speed limitations of active feedback loops (Hollerbach, 1985b) Quiescence may also prevent the initial steep rise in tension due to short-range stiffness which would develop during lengthening of actively contracting muscle at landing (Rack and Westbury, 1974; Flitney and Hirst, 1975; Morgan et al.; 1978), which would be destabilizing.

Variability Profile: The variability profile was established in the joint position domain Limitations imposed by the normalization formula used in the data analysis prevented the variability in the angular velocity and acceleration domains. The normalization procedure was inaccurate in preserving the function of the movement equation during the high transient values at landing for the higher order position derivatives Despite these limitations, the position variability profile was informative in lending some insight into the organization of the landing movement across the three EMG classification groups

The bi-directional variability modulation during the final phase of flight in the AS individual was created by the formulation of a region of consistent positioning at the point of maximum extension for both the knee and ankle joints. This limit positioning was considered to be an actively controlled parameter as the extension limit did not correspond to the biomechanical limit at either joint. The insertion of a region of consistent joint positioning prior to landing was associated with a linearization of the stiffness at the knee and ankle joints during the final phase of flight. In contrast, the uni-directional modulation of position variability in the TS individuals was coupled with an absence of a linear stiffness profile and consistent positioning for the final movement phase However, in the younger PDS individuals, joint biomechanical limit positions were used to generate the linear stiffness. These limit positions therefore appeared to effectively substitute the nodal region of variability modulation. However, in these younger PDS individuals, consistent features of the final movement phase required an increase in muscle work as represented by the positive power curves at all three joints and possibly increased compressive forces due to extension positions at landing.

The region of critical joint position in the AS profile may represent the minimum of active control which is required to yield a successful landing position. The nodal region may allow some preconditions to be achieved once a set of parameter for landing can be assumed to be valid. This definition of movement behaviour would tend toward the predictive model of motor control proposed by Zanone (1990). The time regions of critically decreased variability would represent epochs of kinematic stability that are used as absolute reference points from which the next phase of the motor strategy can be accurately estimated and evolved Functionally, the nodal region may maximize the adaptability of the movement output by allowing a specific reference from which a window of stability can be evaluated, while maintaining the computational requirements to a minimum. The variability interval subsequent to the node is considered as the limit of 'noise' of the position parameter that the system can address and maintain the accuracy and stability of the output. Based on the variability interval, the limits after which point failure occurs and another strategy must be evolved can be identified (McKinley and Pelland, 1993). The existence of these confidence limits would suggest the existence of a method of control of the variability itself. This would limit the noise in the motor system and allow a stable range of effector strategies to be expressed (Pelland and McKinley, 1991).

If the variability profile is considered as an index of increasing efficiency in the organization of the landing strategy, skill would be defined as the emerging ability to control joint position during discrete epochs of flight. This may reflect the minimum amount of information that is required to evolve an efficient motor solution and the time period in which it is critical for its successful adaptation The variability profile indicates the importance of integrating both the temporal and the spatial aspects of the motor strategy. Thus, not only is the joint configuration during certain phases of flight meaningful, but also the timing of these joint positions is crucial for the emergence of landing skill. The variability profile therefore provides an indirect view of the organizational capacity of the system which is not available from simply a discrete evaluation of the movement. Upon refinement, the variability profile may serve as a functional tool for evaluating skill in children, approximating the organizational strategies which are available to the child to cope with different sets of external and internal conditions on different trials of the jump-down.

5.3 Model for Generating Critical Values:

A peculiarity of movement is that it is initially sketched as a general motor plan in three-dimensional kinematic language and yet, the output is usually precise in displacement, speed, and time Gelfand et al. (1971) suggested a time varying computation of the movement profile to allow a space/time precision of the output, details of the movement emerging at the various levels of computation. At each level of processing, the action plan could relate its dynamics both adjacently and successively as the serial nature of the movement arises from the differentiation of a general motor plan (Bernstein, 1967; Evarts et al, 1971). Consequently, the time varying computation would be adaptive in nature, allowing motor organizations to be modified on an ongoing basis to meet the dynamic external and internal conditions without compromising the specificity of the movement. In reality, a continuous computational scheme for all movements would be cumbersome, requiring that a large number of degrees of freedom be addressed to assure movement specificity. Simplifying strategies have been proposed to reduce the computational requirements (Bernstein, 1967; Gibson, 1966; Turvey and Greene, 1972; Nashner and McCollum, 1985; Kugler et al., 1980; Kelso, 1982; Gottlieb, 1990). These are heuristic behaviour which rely on critical values for the organization of a specific movement profile. Boden (1987) has suggested that criticality levels are provided in the data base rather than being actively estimated by the program itself. Therefore, an object of developmental learning may be the definition of these critical values for frequently performed movement organizations and may evolve through the gradual correlation of a movement to its sensory consequences (Thelen, 1990 and 1991).

A developmental model for the organization of movement is presented in Figure (19B). The model is based on the variability profile analysis, specifically on the formulation of the region of critical positioning in the final phase of flight. The model is schematic and therefore does not address realistic feedback delays or internal stability problems. It is put forth as to possibly contribute to the understanding of the difficulties encountered by some children in effectively organizing appropriate movement profiles. According to this model, the system would be required to specify critical movement parameters only over critical time regions. The critical time regions are identified as the 'comparative node'. The comparative node represents a region during the movement differentiation where preconditions, both environmental and biomechanical, are assessed and compared to the efferent copy. The comparative node would therefore function as an evaluation/decision base, providing predictive information for prospective planning of the subsequent movement phase. The comparative capacity of the node requires an integration of available internal and external conditions (feedback control) as well as of the predicted behaviour (anticipatory control).

From the comparative node, a predictive coding envelope for the subsequent movement phase is established. The limits of the predictive envelope could be calculated through extrapolation along the lines of the variability profile. Therefore, the end result of the processing at the comparative node would 'set' the bandwidth of the predictive envelope, and define the range of internal and external conditions that could successfully be accommodated by the musculoskeletal parameters without evolving a new movement organization. If the behaviour is predicted to be either at or beyond the available biomechanical limit, a new movement organization would be evolved. Feedback may therefore be particularly valuable along the limits of the predictive coding envelope, such that predictive behavior does not preclude the ongoing influence of feedback control during all phases of the movement execution. For the landing task, the predictive coding envelope would be important to control the impact ground reaction forces. This is important as the passive forces at landing would typically occur within 50 ms and therefore be applied too rapidly to be effectively addressed by pure reflex activity (Lees, 1981; Devita and Skelly, 1992).

The sensitivity of the nodal regions to anticipatory and feedback information underlines the increasing efficiency in generating a predictive coding envelope as the capacity for sensorimotor integration increases. The predictive capacity of the comparative node and the subsequent predictive coding envelope would therefore evolve in parallel to the increasing capacity for sensorimotor integration during development. This is hypothesized from results of persistent difficulties in timing muscular activity for postural control in young children (Lee and Aronson, 1974; Butterworth and Hicks, 1977; Forssberg and Nashner,1982) and in children with vestibular deficits (Horack; Black;). Through developmental learning, the comparative node would gradually generate wider confidence intervals of the predictive coding envelope for which a given movement organization will provide stability. As the confidence intervals decrease, there arises a need to evolve new movement organizations for small changes in internal and external conditions, representing an increased computation for movement specificity. When the actual movement outcome is beyond the limits of the predicted envelope, feedback mediated stretch reflexes may be invoked to provide stability. Therefore, a narrow predictive coding envelope should theoretically be associated with a default movement strategy which would bias stretch-mediated reflexes as there would be a high probability that the actual movement output will be outside the limits of the predictive envelope. A default strategy could represent a functional compromise between the stability requirements and the adaptability requirements of a movement organization, as 'adaptability without stability is of little use' (Patla, 1990).

From a developmental perspective, the development of controlling parameters would determine the interaction between the general motor plan and the predictive behaviour. The controlling parameters include development at both the sensorimotor and biomechanical level and would be reflected in the movement profile at the muscle (EMG), kinematic, and kinetic levels of the organization. These three movement parameters are schematically represented in Figure (19A). The illustrations suggests a scalar progression of the muscle, kinematic, and kinetic parameters during development. As represented on different scales, the development of the three parameters could be independently specified. Therefore, there exists the possibility of either a coeval development during childhood or that one component may 'lead' or 'lag' the others during certain periods of development. The motor 'clumsiness' observed in certain children may arise from a disassociation of the three movement components such that an equivocal scalar position is not observed for all three parameters. Seefelt and Haubenstricker (1982) support the idea that the progression from one stage of development to the subsequent stage would occur on a continuum of development, with consolidation among characteristics around a point on the continuum. Thus, all of the subroutines within a stage would not develop as an indivisible unit or in lock-step fashion.

From this model, skill would be related to an increase in the predictive coding capacity, allowing a greater adaptability of the effector strategy. This hypothesis can be probed through experimental perturbations, thereby establishing the limits that can be accurately predicted and thus serviced by a specific motor organization. The motor behaviour at the limits also reflect the problem-solving capacity of the system. This raises the possibility that in rehabilitation, there may be a need to increase sensory information prior to the comparative node, with the aim of increasing the predictive envelope rather than decreasing it (making the output stereotypic).

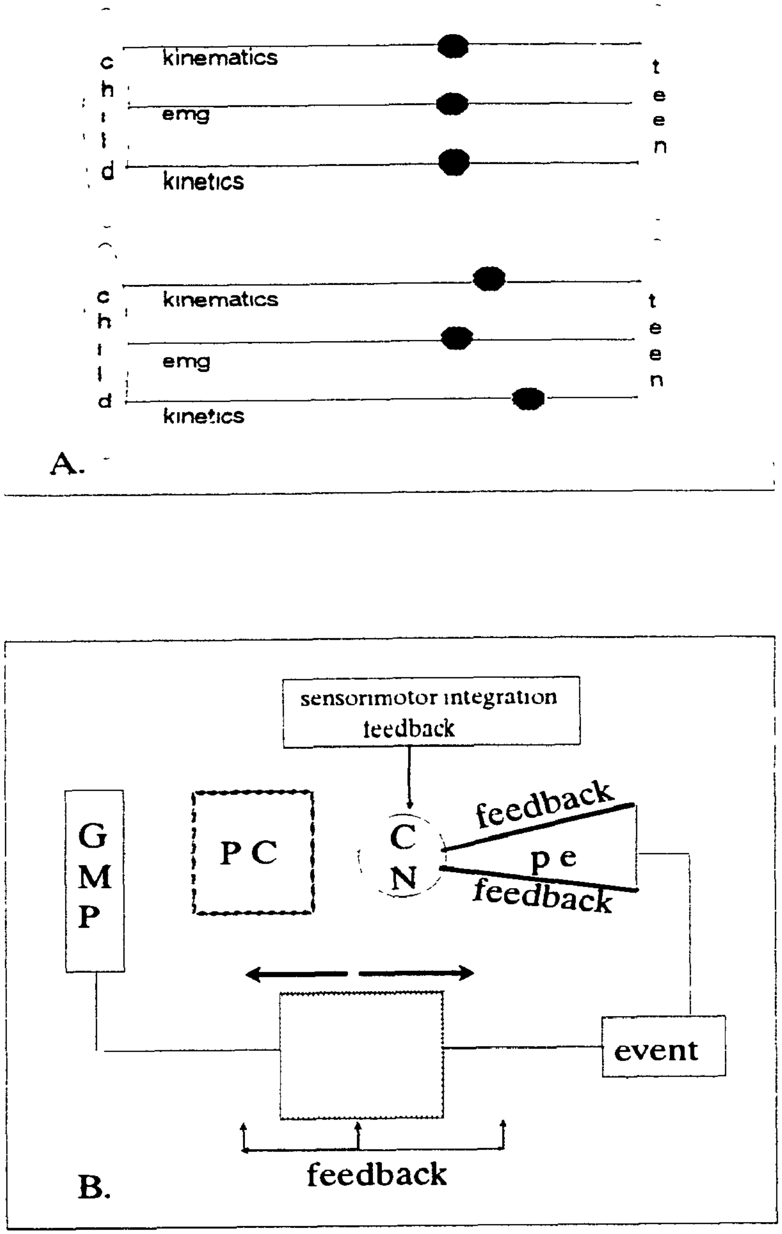
5.4 Relevance of the Motor Solution:

There appears to be a limit to the functionality of the PDS and TS strategies for older subjects. For the two older subjects in the PDS group, FB and MR, the PDS strategy was not effective in controlling the impact ground reaction forces. This poor performance of the landing skill was associated with a low performance index on the Bruininks-Oseretsky motor developmental scale (31st percentile). The complete assessment of the parameters contributing to the poor motor performance of these children is the focus of another paper.

Figure 19A. Continuum between childhood and teen years represented for: A) kinematics, **B)** EMG, and C) kinetics.

Figure 19B. Proposed Model for the contribution of predictive behavior to the development of motor strategies.

DEVELOPMENTAL MODEL FOR MOVEMENT ORGANIZATION



CHAPTER SIX: SUMMARY AND CONCLUSIONS

Performance index on developmental test batteries, such as the Bruininks-Oseretsky Test of Motor Proficiency, are often used as independent indicators of sensorimotor development. However, these developmental test do not address the quality of a movement (EMG and Kinematics) nor the evolution of the movement organization as coordination increases. The purpose of this study was to define an analysis of the muscle and kinematic parameters which are sensitive indicators of the emerging movement organization for the landing task. The focus was on the organization of the movement of the lower extremity during flight in terms of their efficiency in anticipating the impact ground reaction forces. Efficiency was evaluated from the peak vertical acceleration forces at the iliac crest experienced at impact and from the postlanding stability profiles.

The central finding of the study was the classification of nine boys 7 years to 13 years of age into three distinct groups based on the profile of muscle onsets in anticipation for landing: the PDS group, the TS group, and the AS group. Accompanying kinematic parameters also were found that were useful descriptors of the group into which a subject was classified. In particular, joint operating range, joint coordination patterns, and the use of limit positions were found to be simple, yet valid correlates of the EMG classifications. All of these parameters are incorporated in the joint position variability profile of the ongoing movement. The variability profile summarizes the time varying computation of all the kinematic parameters as they relate to the control of joint position. Therefore, movement analysis using a variability profile may serve as a basis for developing a clinically based measurement tool which addresses both the quantitative and qualitative nature of the movement organization. Consequently, the profile may serve to define those aspects of a movement which contribute to poor motor performance.

6.1 Limitations:

The following limitations should be considered in the interpretation of the results of this study:

1) First, the emerging properties of the landing skill were evaluated in only nine subjects. However, consistent organizational patterns could be identified across this limited subject pool, underlining the stability of the measurement parameters selected for the analysis.

2) The movement was analyzed for only one leg and thereby does not address interlimb coordination strategies. It is recognized that the ability to manage and organize the active and passive forces simultaneously in the two limbs will further contribute to the developmental differences in the computation of movement profiles.

3) The emerging strategies were defined in terms of a static model relating muscle activity and kinematic parameters. A dynamic model would be useful to address the kinetic profiles associated with the distinct movement organizations to determine the interaction of the active and passive (motion-dependent) forces during the different stages of growth and development.

6.2 Recommendations for Further Research:

Further research projects should address the following issues:

1) The role of age versus experience (or training) should be investigated on a larger cohort of healthy children to ascertain with confidence the normal developmental progression of the landing task and thereby validating the classification scheme presented in this thesis.

2) The identified indexes of motor organization across the three classification groups should be correlated more specifically to the Developmental Test Scores to determine the parameters which would be more closely associated with a poor or inefficient motor performance.

3) The analysis approach should also be addressed in the dynamic domain to determine with more validity the self-organizing qualities of the movement. This would particularly be informative when considering that the difficulty of younger children to deal with motion-dependent forces could be identified at the static kinematic level. The time-varying interplay of active and passive (motion-dependent) forces during the movement execution across the three classification groups using quantitative tools such as Power Flow Analysis (Winter, 1990) and Energy Absorption Analysis (Cincerra and McKinley, 1993).

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