Classical ballet training and the control of upright balance

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August, 2003

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Doctor of Philosophy (Rehabilitation Science)

Your file Votre référence
ISBN: 0-612-98276-9
Our file Notre référence
ISBN: 0-612-98276-9

Abstract

The control mechanisms used by the central nervous system to maintain posture during changes in the base of support are not well understood. Two components, one proactive and one reactive, have been shown to contribute to balance. However, the way in which these elements are utilized for the control process is not clear. Athletic training, particularly in sports which require well-defined controlled movements, positively impacts the control of posture. Few studies have addressed the contribution of dance training on postural control and these results were inconclusive. Thus, the present goal was to contrast dancer and non-dancer strategies for the maintenance of upright balance. This study assessed postural control during multi-directional voluntary (leg lifts) and involuntary (surface tilts) weight shifting. Eleven classical ballet dancers and nine matched athletic non-dancers were recruited. Each participant performed five blocks of fast leg lifts in ten directions and maintained stance during five blocks of surface tilting (10° at 53°/s) in eight directions. A six-camera VICON 512 imaging system was used to determine 3-D body movement (120 Hz). To establish muscle activation patterns, EMG from four right leg muscle pairs was recorded at 1080 Hz. Simultaneously, two AMTI force plates measured ground reaction forces (1080 Hz). Group differences were evaluated by analysis of variance and principal component analysis. These experiments showed that control system redundancy is reduced through the recruitment of specific postural strategies that are selected based on the task goal. Limb unloading, voluntary or unexpected, requires control of the total body center of mass. During voluntary leg lifts, dancers and non-dancers achieve this goal differently. Dancers maintain vertical trunk alignment whereas non-dancers use changes in trunk orientation to generate movement and control COM displacement. In contrast, surface tilting produced stereotypical postural responses that were only slightly modified in dancers. Segmental coordination and EMG patterns revealed dancer response to be more influenced by perturbation direction, which may be the result of long-term training. This dissertation has contributed to our understanding of the plasticity of the postural control system with particular emphasis on the effects of task demands and ballet training on response strategies.

Résumé

Les mécanismes de contrôle utilisés par le système nerveux central dans le maintien de la posture lors de perturbations impliquant des changements de la base de support, ne sont pas très bien connus. Il a été démontré que l'équilibre comporte deux composantes, une proactive et une réactive. Cependant, la manière dont ces composantes sont utilisées dans le contrôle de l'équilibre demeure inconnue. Le contrôle de la posture peut être amélioré par l'entraînement physique impliquant surtout des sports dont les mouvements sont définis et doivent être contrôlés. L'effet de l'entraînement à la danse sur le contrôle de la posture est très peu étudié et les résultats disponibles jusqu'à maintenant sont peu concluants. Ainsi, le but de ces études était de comparer les stratégies utilisées dans le maintien de la station debout, chez des danseurs ayant reçu une formation en ballet classique ainsi que chez des sujets contrôles. Les travaux présenté dans le cadre de cette thèse ont évalué le contrôle de la posture lors de transferts de poids effectués volontairement (levée de jambe) ou involontairement (mouvement de bascule du plancher) dans de multiples directions. Onze danseurs de ballet classique et neuf sujets contrôles pairés ont participé à cette étude. Tous les sujets ont complété cinq blocs de levée de jambe, exécutée rapidement, dans dix différentes directions. Ils ont également maintenu leur équilibre lors de cinq blocs de mouvements de bascule du plancher, effectués dans huit directions différentes (10° à 53 °/s). Un système d'enregistrement vidéo à haute vitesse VICON 512, comprenant 6 caméras, a été utilisé pour mesurer le mouvement du corps en trois dimensions (120 Hz). L'activité électromyographique de quatre muscles complémentaires de la jambe droite a été enregistrée à une fréquence de 1080 Hz et ce, afin de déterminer les patrons d'activation musculaire. Simultanément, deux plateformes de force AMTI enregistraient les forces de réaction au sol (1080 Hz). Les différences entre les groupes ont été évaluées à l'aide d'analyses de variance et d'analyses en composantes principales. Ces expériences ont démontré que le recrutement de stratégies posturales spécifiques, sélectionnées en fonction de la spécificité de la tâche, contribue à réduire la redondance du système de contrôle. De plus, le centre de gravité du corps doit être contrôlé afin de permettre l'allègement de la jambe. Les danseurs et les sujets contrôles effectuent les levées de jambe volontaire différemment. En effet, les danseurs maintiennent leur tronc aligné à la verticale tandis que les sujets contrôle modifient l'orientation de leur tronc, ce qui leur permet d'exécuter le mouvement de la jambe et contrôler le déplacement de leur centre de gravité. Toutefois, le mouvement de bascule du plancher induit des réponses posturales stéréotypées qui sont très peu modifiées chez les danseurs de ballet. La modulation de la réponse à la perturbation dépendait plus de la direction de cette dernière chez les danseurs, tel que démontré par la coordination des mouvements et les patrons d'activation musculaires. Cette différence entre les danseurs et sujets contrôles est probablement due à l'effet d'un entraînement à long terme. Cette thèse de doctorat a contribuée à notre compréhension de la plasticité du système de contrôle postural avec une emphase particulière sur les effets des demandes de la tâche et de l'entraînement au ballet sur les stratégies de réponse.

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This thesis is presented in a manuscript-based format in accordance with the Guidelines for Thesis Preparation described by the Faculty of Graduate Studies of McGill University (revised March 2003).

I attest to the fact that this thesis contains no material previously published or written by another person except where referenced.

Contribution of Authors

Listed below are the articles included as part of this dissertation and an outline of the responsibility of each author. Overall, Dr. Fung was both thesis supervisor and critical reviewer to Ms. Hughey.

Chapter 3

Hughey L.K. and Fung J. Postural responses triggered by multi-directional leg lifts and surface tilts. Submitted to: *Exp Brain Res.* May 2003.

Chapter 4

Hughey, L.K., McKinley, P. and Fung, J. The control of upright balance in skilled ballet dancers and recreational athletes: I. multi-directional leg lifts. Submitted to: *J Neurophysiol.* August 2003.

Chapter 5

Hughey, L.K., Fung, J. and McKinley, P. The control of upright balance in skilled ballet dancers and recreational athletes: II. multi-directional surface tilts. To be submitted to: *J Neurophysiol.* August 2003.

Ms. Hughey designed the experimental procedure to quantify postural response to voluntary and unexpected balance perturbations. Ms. Hughey recruited subjects, collected kinematic, kinetic and EMG data and performed all data analyses. The manuscript prepared for publication was written by Ms. Hughey and edited by Drs. Fung and McKinley.

Acknowledgements

I would like to thank my supervisor Dr. Joyce Fung for her guidance and encouragement. I have learned so much during my years at McGill. In addition, I could never have completed this manuscript without the support of Dr. Patricia McKinley who was always there.

Thanks to Rumpa Boonsinsukh, Margherita Rapagna and Caroline Paquette for being terrific labmates and even better friends.

To my ballet students and all the others who participated in this study: you're the stars!

I owe a large debt to my parents and Francia Russell who told me to follow my dreams.

Finally, thanks to my husband and son. You survived a "mommy on the edge". I love you both!

Chapter 1 Introduction

This chapter presents the motivation for this study of the effects of classical dance training on postural control. In addition, the main goals and hypotheses governing the research are stated and the organization of the dissertation is outlined.

1.1 Motivation

Human balance abilities are tested daily in activities as innocuous as getting dressed, commuting to and from work, shopping or even meal preparation. The ability to control posture and maintain equilibrium even in adverse situations is essential. Falls represent a leading cause of injury and morbidity particularly in the elderly population (Figure 1.1). For example, in 1993-94 some 23,375 Canadians in the 60+ year age group sustained hip fractures at a cost of over $980 million. Due to an increasing volume in the older age groups, the number of fractures is projected to reach 88,000 by the year 2041 (Papadimitropoulos et al. 1997). An understanding of the central mechanisms involved in the control of posture and balance is required if the goal of injury prevention is to be realized. It is well established that both feedforward and feedback components contribute to postural stability and when input from either component is lacking, due to disease or aging for example, balance is compromised (Horak and Macpherson 1996; Massion 1992). However, scientific literature pertaining to the integration of these components into centrally generated response strategies is sparse. Therefore, studies which measure anticipatory and reactive response strategies following balance perturbation in healthy young subjects will add to current knowledge and provide a base to which response strategies used by patient populations can be compared.

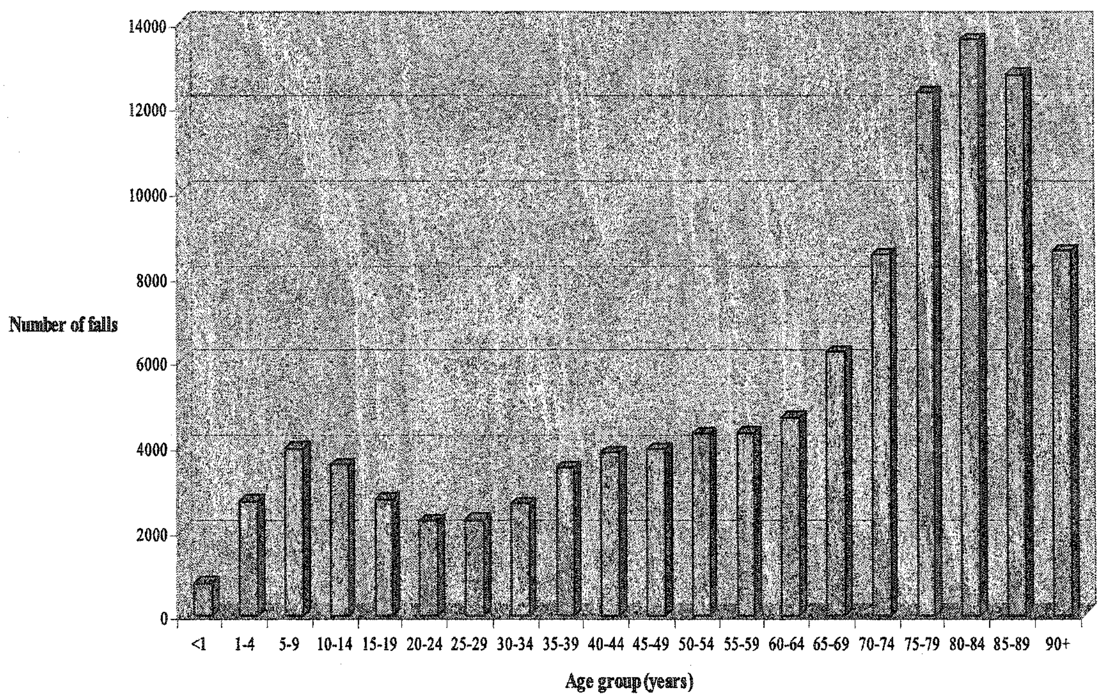

Figure 1.1 Number of hospital admissions due to unintentional falls as a function of age. From: Canadian Institutes of Health Research (CIHR)

Athletic training, particularly in sports which involve well-defined controlled movements and balance activities, positively impacts the feedforward and feedback control of posture and balance (Pedotti et al. 1989; Perrin et al. 2002; Perrin et al. 1999). Classical ballet is a unique endeavor which combines athletic prowess, movement coordination, body stabilization and artistic constraints. Through training, dancers develop an awareness of their body in space. Dancers must be able to adapt quickly to different environmental conditions such as a slippery floor or when blinded by a bright spot light regardless of the specific workspace. To maintain balance in all situations, dancers learn to make use of the available sensory input (Golomer et al. 1999). Ballet training also teaches dancers to build a mental construct of how their individual body segments relate to each other in order to produce a specific movement or posture. By visualizing an end position or movement "shape", dancers execute movement or posture without concern over "how" the movement should be performed. This ability would be particularly useful for patients in which movement and posture are difficult to control such as Parkinson's disease. The performance of each dance step is highly regulated by the rules of the discipline as dictated by each teacher or choreographer. Therefore, it is reasonable to expect dancers to be better able to anticipate upcoming postural instabilities induced by voluntary movement and to respond in a constructive feedforward fashion as compared to untrained individuals. However, the means by which this control is achieved has not been fully demonstrated. Also, the impact of dance training on reactive balance responses is not clear. It is not known whether the observed changes in postural response strategies in dancers to practiced voluntary movements are carried over into triggered responses. Therefore, a comparison study between dancers and non-dancers during voluntary and unexpected stance perturbations will help to establish whether dance training has a positive effect on both proactive and reactive balance skills.

1.2 Project overview and research objectives

The overall goal of this research is to provide further insight into the motor control process in the maintenance of upright vertical posture in humans. Of particular interest are the feedforward and feedback contributions to postural control. The main focus of the project is to quantify postural responses to internally and externally imposed perturbations to the maintenance of stance in classically trained ballet dancers and active non-dancers. Three general hypotheses govern my research in this thesis dissertation:

1) **Stabilization of the body's center of mass (COM) and the coordinated stabilization of the head and trunk complex are the primary controlled variables for equilibrium maintenance under both static and dynamic conditions.** Thus, efficient postural strategies during either voluntary movement or triggered from unexpected perturbation will involve minimization of both COM excursion and deviation of the head/trunk from vertical.
2) **The central organization of postural responses associated with voluntary movement is affected by experience and training.** Through extensive training, dancers develop well-defined response patterns to specific activities such as leg lifting. Therefore, when asked to perform a voluntary task for which they have trained, dancers will complete the movement in a smooth feedforward fashion. Non-dancers, on the other hand, will demonstrate more inter-individual variability and will require longer latencies to facilitate the integration of sensory feedback. In addition, during voluntary movement, dancers will be able to stabilize the head and

trunk in space whereas non-dancers will have more difficulty controlling trunk displacement.

3) **Unexpected, externally triggered perturbation results in stereotypical postural responses which are not affected by training.** Major differences between the groups were not expected. However, elements of the control patterns used by dancers, such as the control of head and trunk verticality, will be carried over into triggered postural response strategies.

To test these hypotheses, two different experiments were performed:

Specific Aim 1: To compare and contrast postural responses in classical ballet dancers and athletic non-dancers during multi-directional leg lifting.

Leg lifting is a common task in classical ballet and its execution is well prescribed. Therefore, dancers are expected to employ a different strategy to preserve postural stability throughout the movement as compared to non-dancers. In particular, the dancer strategy will focus on the maintenance of head and trunk verticality to minimize center of mass displacement. Leg lifting will be produced through feedforward rotation of the pelvis. Non-dancer response, on the other hand, will be more variable and include inclination of the trunk away from the lifting leg in order to control center of mass displacement.

Specific Aim 2: To compare and contrast postural responses in classical ballet dancers and active non-dancers triggered by unexpected multi-directional surface rotations during stance.

When balance is threatened, the central nervous system initially acts to regain postural equilibrium with combined feedback and feedforward control. Discrete response patterns are employed. This study will be used to verify whether the postural strategies adopted during voluntary movement are also used when stance is suddenly and unexpected disturbed. The type of surface rotation will be such that the tilt directions and subsequent limb unloading patterns will be similar to those found during leg lifting. Large differences between the groups are not expected. However, some subtle effects of training on triggered responses may be found. The results of this study will add to our understanding of the effects of classical dance training on balance abilities.

1.3 Dissertation Outline

This dissertation is presented in six chapters which develop the three phases of the research. A review of the neural control of posture and balance, leading to the rationale behind this research dissertation, is given in Chapter 2. In Chapter 3, normal postural response strategies are investigated during voluntary leg lifting as compared to sudden perturbation of the support surface. In Chapters 4 and 5, the effects of long-term classical ballet dance training is examined by comparing the postural response strategies used by dancers and athletic non-dancers during voluntary leg lifts (Chapter 4) and unexpected surface tilts (Chapter 5). Finally, Chapter 6 is a summary of the thesis and suggests directions for future work related to the plasticity of the postural control system and intense athletic training.

1.4 References

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Chapter 2 Background & Significance

2.1 Human Postural Control

Human posture is unique among animals in that the longitudinal axis of the lower limb is colinear with that of the body. The appearance of "stable" vertical bipedal posture is the result. In reality, however, there is curvature associated with the spine and the bones of the lower limb are not truly vertical. Indeed, the multi-linked design of the human body is inherently unstable. Maintaining postural stability, even during quiet stance, is a dynamic task. The body is never quite motionless (Carroll and Freedman 1993). Balance is constantly challenged, not only by gravitational forces, but also by forces resulting from bodily motion and environmental interactions. To counteract these ill effects and avoid falling, the coordinated activity of the musculoskeletal system is required (Allum and Honegger 1992; Allum et al. 1994; Shumway-Cook and Woollacott 1995; Winter et al. 1990).

Injury, disease and aging all have detrimental effects on the control of posture and balance. For instance, a number of age-related deficiencies in postural control have been described. First, consider the loss of range of motion which may be due to disuse, injury (chronic or acute) or inflammation. Loss of range of motion can lead to biomechanical adaptations that adversely affect balance (Romero and Stelmach 2003). Forward trunk flexion, which often accompanies age related diseases such as osteoporosis or osteoarthritis, causes the horizontal projection of the center of mass to move forward, near the edge of the "safety zone" as defined by the feet. Also, elderly subjects, particularly those prone to falling, have been shown to use less hip extension than young subjects during locomotion (Kerrigan et al. 2001). The decreased range of motion adversely affects walking performance by shortening the stride length. Therefore, small perturbations to balance are more likely to have destabilizing effects and result in injury. Decreases in muscle strength and the ability to generate force, both of which have been shown to accompany aging, can also cause reductions in the efficiency of motor response (McGibbon and Krebs 2001; McGibbon et al. 2001). In addition, sensory acuity, the speed with which information is transferred along neural pathways and the ability to adapt to changes in sensory input redundancy are reduced in the aging population (Allum et al. 2002; Hay et al. 1996). Even anxiety brought about by a fear of falling has been shown to adversely affect movement performance (Brown et al. 2002). Therefore, an inverse relationship between postural stability and age has been shown to exist. Similar reductions in balance capabilities have been reported in patients suffering from stroke (Cirstea and Levin 2000; Keenan et al. 1984; Slijper and Latash 2000), Parkinson's disease (Latash et al. 1995; Lee et al. 1995; Marchese et al. 2003; Morris et al. 2001) and spinal cord injury (Janssen-Potten et al. 2000; Leroux et al. 1999; Seelen et al. 2001), among others. An understanding of the basic mechanisms behind the control of posture and balance is essential if effective rehabilitative programs are to be developed.

2.1.1 Postural orientation and equilibrium

Control of posture involves two main functional tasks: postural orientation and postural equilibrium (Horak and Macpherson 1996; Massion 1992, 1994). Postural orientation refers to the spatial relationship of individual body segments to one another and with respect to the environment. These internal frames of reference are essential for bodily perception and for movement performance. Postural equilibrium or balance describes the state in which all forces, internal and external, acting on the segment joints are opposed such that a desired body position is maintained (static equilibrium) or a goal oriented movement is achieved (dynamic equilibrium).

Internal knowledge of segmental positioning is important for both self-awareness and voluntary action (Massion 1992). The performance of a goal-oriented task requires that the position and relationship between body segments be set against some reference value so that spatial targets in the external environment can be calculated and movement or posture can be achieved in an appropriate manner. Three frames of reference have been discussed with regards to postural control (Berthoz 1991; Knudsen et al. 1987; Massion 1992; Paillard 1991; Soechting and Flanders 1989). Spatial information concerning the relationship of one body-segment or limb with respect to another is given by the egocentric reference frame while the exocentric reference system refers to the position of the body within context of the external environment. The geocentric reference frame, considered to be the most important, determines posture based on the vertical gravity axis (Berthoz 1991; Di Fabio and Emasithi 1997). To efficiently reduce instabilities resulting from perturbations to balance, information from the visual, vestibular and proprioceptive systems must be integrated into each reference frame.

Recent research provides strong support for the presence of an internal map or representation in which input from the geocentric, egocentric and exocentric reference frames is organized for incorporation into the motor control process (Gurfinkel et al. 1995). As first described by Head and Holmes (1911-1912), the "postural body schema" is a "combined standard against which all subsequent changes of posture are measured." In other words, the body schema is an internal representation of the body in a state of equilibrium. It is constructed from body segment motion and inertial information as well as from multi-sensory feedback (Clement et al. 1988; Gurfinkel et al. 1995; Gurfinkel et al. 1988). Head and Holmes (1911-1912) further state that the body schema organizes motor activity "before the change in posture enters consciousness." It is used in part to counteract expected balance perturbations.

2.1.2 Sensory feedback systems

The human body is endowed with a multitude of input sources by which to construct appropriate postural responses to control equilibrium including the visual, vestibular and somatosensory systems. Information from these sources must be integrated into the body scheme so that the proper segmental orientation for a specific task given the environmental conditions can be determined (Horak and Macpherson 1996). Each sensory modality offers unique information, however the system is redundant or, more appropriately, "abundant" enough to allow for the absence of one or more inputs (Gelfand and Latash 1998; Lackner 1992; Latash 2000). Furthermore, it is believed that postural stability is optimized through the weighting of one type of input over another (Horak and Macpherson 1996; Horak et al. 1994; Kuo et al. 1998). For instance, by analyzing changes in the center of mass position induced by a sinusoidal rotation of the support surface in patients with bilateral vestibular loss and controls, Creath et al. (2002) showed that control subjects were able to shift input dominance from the somatosensory to the vestibular system as the rate of platform oscillation increased. The patients were unable to make this adjustment as manifested by increased trunk displacement and loss of balance. The weighting of sensory input can also be influenced by task, environmental conditions and the means by which a task is accomplished (Bent et al. 2002; Bronstein 1986; Horak and Macpherson 1996).

Visual information is used by the central nervous system to stabilize the body with respect to the external environment. The effects of vision on postural sway have been studied by numerous research groups. Visual input frequency (Amblard et al. 1985; Kunkel et al. 1998), perception of body vertical (Duarte and Zatsiorsky 2002; Isableu et al. 1997; Van Beuzekom and Van Gisbergen 2000) and training (Perrin et al. 2002; Perrin et al. 1998; Perrin et al. 1997) have all been found to impact the control of posture. One means by which the role of vision in postural control has been assessed is through the use of conflicting visual information. In an early study in which body sway was manipulated by moving the visual surround, Lee and Lishman (1977) showed that vision plays a primary role in the control of balance during stance. As the visual scene was tilted, subjects aligned themselves to the new reference. Sway was induced by displacing the visual anchor. Thomson (1983) has proposed that visual information is used by the central nervous system to control dynamic movement in a discontinuous fashion. He assessed the ability of subjects to walk to a target of varying distances both with and without vision. The results showed that the lack of visual input had no impact on targets up to 5 m away, but when the targets were placed between 6-21 m away, performance was dramatically impaired. Therefore, he concluded that the role of vision was two-fold, depending on the task. For short duration activities, visual input is used to access appropriate motor sequences in advance of actual movement. However, for longer activities, the central nervous system utilizes visual input to formulate an internal representation of the body within the specific environment. Dependence on visual input has also been found to be affected by specific athletic training, such as judo or classical ballet (Perrin et al. 2002).

The vestibular system is comprised of two components, the semi-circular canals and the otolith organs which measure angular and linear accelerations of the head, respectively (Gresty and Bronstein 1992; Tomko and Paige 1992). Therefore, due to vestibular input which serves to facilitate the processing of visual information, feedforward stabilization of the head in space can be achieved (Assaiante and Amblard 1993; Berthoz et al. 1979). Another important function of the vestibular system is gaze stabilization. The otolith organs provide a reference for head position with respect to the vertical gravity vector. Thus, through ocular reflexes, gaze is stabilized by the counter-rotation of the eyes relative to the head. Vestibular input is believed to provide the gravitation information necessary to create an internal reference for body vertical (Gurfinkel et al. 1995). Kaufman et al. (2001) were able to demonstrate the use of gravitoinertial information by the central nervous system in the creation of an internal reference frame. Eye movements, center of pressure and body kinematics were recorded while seated healthy and vestibular-deficient individuals were asked to perform head saccades towards a lighted target in a darkened room. Errors were measured in perception of head-vertical by all subjects. It was concluded that both orientation and magnitude of the gravitoinertial vector are used to determine body vertical. Without vestibular input, feedforward control of the head is lost (Pozzo et al. 1990). Reschke et al. (1994) reported that after a period of weightlessness, astronauts displayed difficulty in coordinating the head and trunk during locomotion. They suggest that the lack of gravity in space caused a recalibration of the otolith gravity receptors such that feedforward control was compromised. Vestibular inputs can also affect trunk and limb stability. For instance, Horak et al (1990) compared the postural response of vestibular-deficient subjects to controls during quiet stance and while standing on a narrow beam. The control subjects were able to use a hip strategy to maintain balance as the difficulty of the task increased whereas the vestibular loss patients where unable to change control strategies. Use of the hip strategy involves active stabilization of the head in space as the trunk and pelvis counter-rotate. Thus, without vestibular input, knowledge of head orientation or planned trajectory is difficult at best.

The somatosensory system includes muscle proprioception as well as joint and cutaneous afferents which provide the central nervous system with information concerning body orientation and equilibrium. One advantage that the somatosensory system has is that, unlike the visual and vestibular systems which are located in the head, its sensors are distributed throughout the body. The somatosensory system provides critical information concerning the orientation of individual body segments with respect to one another and the environment, i.e. egocentric and exocentric reference frames (Gurfinkel et al. 1995). Proprioceptive information from neck afferents has been shown to be used by the central nervous system to derive trunk position (Allum et al. 1998; Keshner et al. 1988; Keshner and Peterson 1995). Since the trunk represents approximately 2/3's of the total body mass, control of trunk orientation is paramount for the control of posture and balance. Mittelstaedt (1992; 1995) has proposed that, in addition to vestibular input, graviceptors originating in the internal organs are utilized to calculate the geocentric reference frame for the control of upright posture. Mechanoreceptors under the feet provide indispensable data about support surface characteristics. Shifts in body alignment have been induced by vibration of ankle muscle groups (Kavounoudias et al. 1999) and vibration of the foot soles (Kavounoudias et al. 1998). When sensation at the feet and ankles is eliminated, stance control remains unchanged. However, perturbation of the support surface generates increased sway patterns. Inglis et al. (1994) studied the postural reactions of patients with diabetic peripheral neuropathy and a group of control subjects to surface translations at various velocities and amplitudes. EMG onset latencies of shank, thigh and trunk muscles were delayed by as much as 30 ms in the patient population. In addition, the patients were unable to adjust joint torques to accommodate the varying perturbation characteristics. It was concluded that somatosensory information from the legs is used for both sensory feedback and the accumulation of experience. Athletic training has been shown to induce a shift from the dominance of the visual system to proprioceptive input during static and dynamic balance tasks (Golomer et al. 1999; Perrin et al. 2002). A more detailed description is presented in Chapter 4.

A model for postural control which involves the interaction of the three sensory inputs into one global reference system has been proposed by Mergner and Rosemeier (1998). The sensory integration model involves the central control of posture through upward channeling of proprioceptive information from foot contact with the support surface as well as down channeling of visual and vestibular information from the head. Through the synthesis and weighting of this information the central nervous system is provided with an accurate internal model of the position and movement of the body in space in addition to information concerning the viability of the support surface. The weighting of the individual inputs is driven by environmental factors. Control is dominated by proprioceptive information when the support surface is firm and stable whereas if the support surface is unstable (i.e. small or compliant) then visual and vestibular input gain importance (Ivanenko et al. 1997). It would follow then that high-level training in sports such as gymnastics or dancing which boast balance as major performance criterion should improve the execution of voluntary movement and balance control by strengthening the accuracy and importance of proprioceptive inputs, which is a major rationale behind this research dissertation (see Chapter 4).

2.1.3 Postural control strategies

The central nervous system relies on a number of components to efficiently control posture: reference values upon which postural frameworks are built (i.e. postural orientation and equilibrium), multi-sensory inputs that guide orientation and equilibrium (visual, vestibular and somatosensory), and centrally generated rapid balance responses (Massion 1994). A schematic diagram is shown in Figure 2.1. Postural responses are triggered by unexpected perturbation (reactive) or in advance of expected perturbation (anticipatory). To control upright stance and dynamic movement, the control variables are selected and activated according to a high-level response plan, or "postural control strategy".

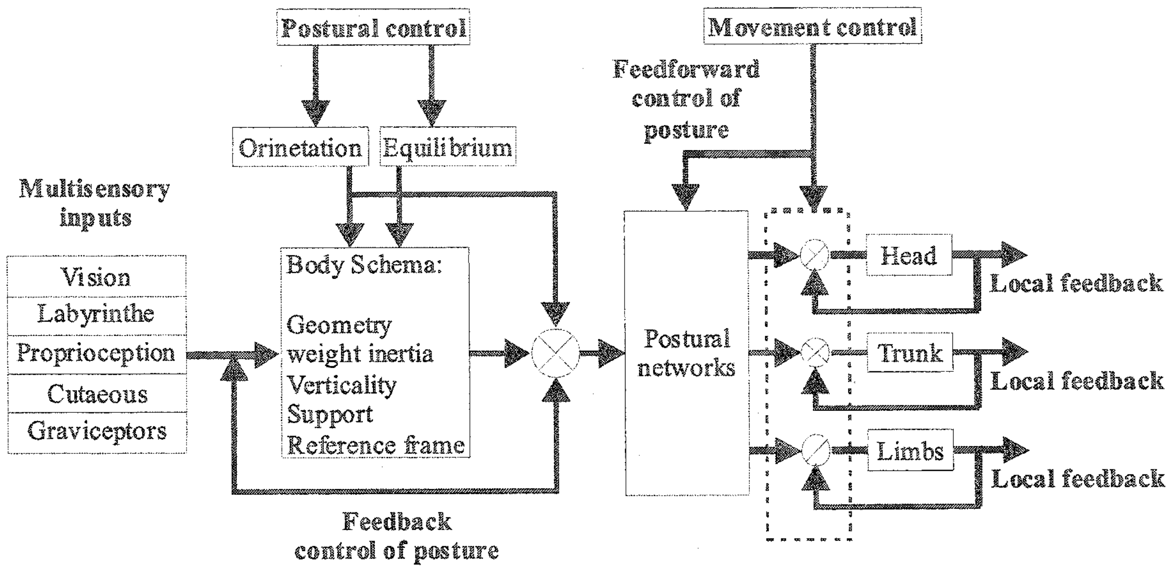

Figure 2.1 Central organization of posture (adapted from Massion 1994)

The redundancy of the motor control system provides the central nervous system with options for solving any given postural task. In other words, there are more degrees of freedom in terms of potential muscle activation patterns, segmental arrangements and kinetic adjustments than are required to perform the task (Bernstein 1967). Only one strategy must be selected from a continuum of possible responses for each movement. Redundancy is one of the primary reasons for the outstanding flexibility of human motor control (Bernstein 1967).

The idea of "postural strategies" was first introduced by Nashner and colleagues (Horak and Nashner 1986; Nashner and McCollum 1985). Depending upon the constraints of the task, subjects were found to respond to stance perturbations in one of two ways: either by flexion at the ankle joint (ankle strategy) or the hip joint (hip strategy). It is important to note that subjects were instructed to avoid knee flexion which would have led to a more complex kinematic strategy. The ankle strategy, shown in

Figure 2.2, involves repositioning of the center of mass through rotation of the body about the ankle joint such that movement at the hip and knee joints is minimized. The ankle strategy is generally used for resisting small, slow perturbations on a wide solid support surface. The hip strategy, on the other hand, uses flexion or extension at the hip to control center of mass displacement (Figure 2.2). It is a common response to fast, large balance perturbations or when the support surface is compliant, unstable or small. When the perturbation is exceptionally large or very fast, a stepping strategy is used (Do et al. 1982).

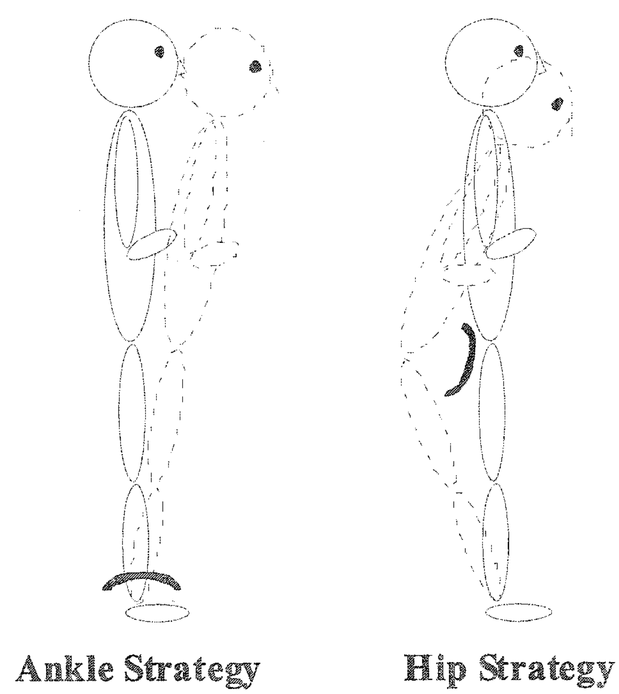

Figure 2.2 Ankle and hip strategies for stance equilibrium (modified from Horak and Macpherson 1986)

The choice of strategy is influenced by feedback from the visual, vestibular and proprioceptive sensory systems which monitor the current or upcoming state of stability (refer to Figure 2.2). In addition, the central nervous system refers to a set of appropriate postural responses or synergies, as first described by Ioffe (1973). This repertoire of muscle activation patterns is stored in memory from a very early age (Eliasson et al. 1995). In terms of motor development, it is believed that the feedforward control processes appear and are built-up more slowly than feedback control (Haas et al. 1989). Insufficiency in the feedforward component is believed to be a major cause of instability in young children (Hay and Redon 1999, 2001). Ledebt et al. (1998) analyzed the anticipatory postural adjustments during gait initiation in children ranging from 2 ½ to 8 years of age. They found that, although anticipatory response was present in the youngest subjects, displacements of the center of pressure and the amplitude of response increased with age. Tuning of feedforward control was concluded to be an ongoing process. In addition, postural synergies are believed to be "flexible" rather than fixed in nature (Henry et al. 1998b; Macpherson et al. 1986). Training, task, instruction and experience all contribute to the development of postural synergies. For example, Pedotti et al. (1989) found that during upper trunk bending, gymnasts used a different strategy for maintaining balance as compared to untrained subjects. When asked to perform the same movement on a narrow support, gymnast response showed adaptation (by way of suppression of the anticipatory component) whereas this response was missing in the untrained subjects. The flexibility of the EMG pattern was believed to be the result of short and long-term training. Flexibility in muscle synergies has also been found in triggered postural responses (Henry et al. 1998b) and in the shift from an ankle to hip strategy when subjects were asked to reduce the size of the base of support during surface translations (Horak and Nashner 1986). Thus, both feedforward and feedback input contribute to the maintenance of balance and equilibrium.

2.2 Controlled variables

When a body is perturbed during stance either by a self-initiated movement or by an external source, postural response generally results in a shift back towards the initial posture (Nashner 1976), assuming that the perturbation does not exceed the bounds of stability (Maki and McIlroy 1997; Pai and Patton 1997, 1998). The way in which the central nervous system achieves this control is still not understood. In order to gain further insight into the control of posture a number of theoretical models have been proposed.

One of the earliest control theories developed was the reflex theory (Sherrington 1906). The reflex theory states that movement is the result of a chain of reflex activities starting from one initial external event. This theory is elegant in its simplicity, but at the same time simplicity is its limiting factor. The reflex theory cannot account for the ability to perform a wide range of goal directed movements or the ability to perform movement in the absence of sensory input since reflexes are a system requirement.

In response to the inherent problems of the reflex theory, the hierarchical theory of motor control was proposed by Jackson in 1932 (Walsche 1961). Instead of control being reflexive in nature, it was assumed to follow a "top-down" behavior in which the cerebral cortex executes commands based on motor plans or programs which are stored in memory. However, in early versions of the hierarchical control model, it was believed that motor programming was uninfluenced by peripheral feedback; everything was predetermined. The question then arose: how are new movements learned if each movement has its own unique motor plan?

Thus, a generalized motor programming theory was developed (Carter and Shapiro 1984; Forssberg 1985; Schmidt 1975). Based on the hierarchical model, control of movement is achieved through adaptation of "prefabricated" programs, either learned or inherited, by sensory feedback. Because the basic control program is part of a central "set", a lack of sensory input does not preclude movement execution. Reflex behaviors are incorporated into the programming model as relatively rigid, rapid response plans. Motor learning is thought to enhance performance by providing feedback from past experience.

Bernstein proposed a systems-oriented approach in which control was a shared process (Bernstein 1967). Low-level reflexes as well as higher-level pattern generators and movement synergies work in concert to simplify the control process, thus reducing the degrees of freedom. In addition, environmental constraints are believed to affect postural response due to their influence on movement mechanics. Bernstein's original model has been modified to include the concept of self-organization. In the dynamical action theory, the dominance of one control variable can shift among various inputs (Kamm et al. 1990; Kelso and Tuller 1984; Schoner and Kelso 1988).

Therefore, to simplify the central control of upright vertical posture and balance, and help solve the degrees of freedom problem (see section 1.2.3), an internal reference value upon which stability is gauged is indicated. Two different hypotheses have been proposed. The first declares that posture is maintained through control of the total-body center of mass (Massion 1992, 1994; Massion et al. 1998; Massion et al. 1997) while the other states that body orientation in space is controlled (Hlavacka et al. 1996; Pozzo et al. 1995). Evidence in support of both hypotheses has been found.

2.2.1 Control of center of mass and center of pressure

Center of mass (COM) is the point at which the total-body mass is balanced and where the sum of the external forces acts (Winter et al. 1990). Total-body COM is defined as the weighted average of the COM of each body segment:

$$CM_i = \frac{\sum_j m_j * p_{i,j}}{\sum_j m_j}, \tag{2.1}$$

where m_j is the mass of segment j, and $p_{i,j}$ is the i^{th} component (i=x,y,z) of the position vector of its center of mass. Movement of any segment will induce a shift of the total-body COM in space. Many forces act to destabilize the body such as forces due to gravity, forces related to environmental interactions and forces generated internally through segment motion. Regardless of the source, any force can cause an acceleration of the body's COM that must be controlled if balance is to be sustained. In static conditions, the laws of physics dictate that the projection of the COM onto the horizontal plane must lie within the base of support as defined by the feet (Winter 1990). Since the human body is never truly static, Pai et al. (1997, 1998, 1999) have proposed a dynamic stability model in which stability boundaries are established based on the interaction of COM position and displacement velocity.

Active displacement of the COM is achieved through the application of force against the support surface. The resultant of these ground reaction forces in the horizontal plane is termed the center of pressure (COP):

$$COP_{A/P} = M_y / F_z, \tag{2.2}$$

$$COP_{M/L} = M_x / F_z, \tag{2.3}$$

where M_x is the moment about the x-axis, M_y is the moment about the y-axis and F_z is the vertical force. When two force plates are used to measure ground reaction forces, total COP excursion can be described by the weighted sums of the forces under the right (R), and left (L) foot:

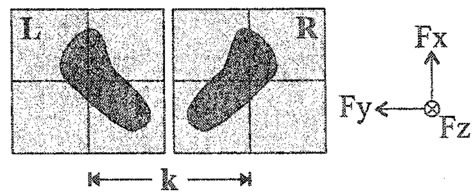

Figure 1.4 Force platforms.

$$COP_{Total_{A/P}} = \frac{LCOP_{A/P} * LF_z}{LF_z + RF_z} + \frac{RCOP_{A/P} * RF_z}{LF_z + RF_z}, \quad (2.4)$$

$$COP_{Total_{M/L}} = \frac{k/2 + RCOP_{A/P} * RF_z}{LF_z + RF_z} - \frac{k/2 + LCOP_{A/P} * LF_z}{LF_z + RF_z}, \quad (2.5)$$

where k is the distance from the center of force plate R to center of force plate L, see Figure 1.4 (Henry et al. 1998a). Postural control during quiet stance is achieved through manipulation of the position of the net COP. COP excursion is primarily controlled through the regulation of joint stiffness (Winter et al. 1990; Winter et al. 1998). The relationship between COM and COP has been described in detail by Winter et al. (1996). In essence, displacement of the COP precedes and exceeds that of the COM. COM trajectory is encompassed or corralled by the COP.

COM stabilization has been used to explain different postural strategies associated with changes in the base of support (Mouchnino et al. 1992; Vernazza-Martin et al. 1999), voluntary movements (Alexandrov et al. 1998; Toussaint et al. 1997a; Toussaint et al. 1997b) and environmental conditions (Massion et al. 1997). Active control of COM displacement has been shown in experiments involving voluntary trunk flexion both with and without an addition load (Vernazza et al. 1996). Despite theoretical calculations which determined optimal anterior/posterior COM travel distances of 8-9 cm, subjects demonstrated only a 1-2 cm shift in actual distance. Segmental adjustments at the hip and ankle ensured COM stabilization. Massion et al. (1997) found that in microgravity conditions, erect vertical posture involved a 7° forward inclination of the torso whereas the COM position was maintained.

Clear evidence of the central control of the COM can be seen in tasks involving adaptation of the support configuration. For instance, lifting one foot will decrease the base of support substantially and induce a fall if the COM is not repositioned over the stance foot. An increase in the ground reaction forces under the unloading limb, which serve to propel the COM towards the loading limb, has been shown to precede limb unloading and scale according to the distance that the COM must travel in order to reestablish posture and equilibrium (Lyon and Day 1997; Mille and Mouchnino 1998). This anticipatory response is not found during supine leg lifting (McIlroy et al. 1999), during leg lifting in microgravity (Mouchnino et al. 1996) or in young children (Ledebt et al. 1998).

COM stabilization is not only associated with postural control during voluntary movement, postural reactions to external perturbation also involve control of the COM. For example, Gollhofer et al. (1989) presented standing subjects with toes-up rotation of the support surface. The axis of rotation was either even with or below the ankle joints. Thus, in the latter condition, a translational component was added. The researchers found that shank muscle response varied between the two tasks such that as translation was added, the pattern of response shifted from tibilais anterior dominance to activation of the gastrocnemius. Since dorsiflexion of the feet is followed by backwards displacement of the body, activation of the anterior shank muscles serves to keep the horizontal projection of the COM within the base of support. However, during backwards translation, if the goal is to control COM positioning, gastrocnemius activation is required to restore correct positioning.

2.2.2 Head and trunk orientation

There is growing evidence that the central nervous system actively controls trunk orientation. Research performed on cat models has shown that, in quadripeds, the trunk is stabilized with respect to the support surface. Trunk alignment relative to the support surface, as well as intralimb geometry, is maintained throughout support surface rotation (Lacquaniti et al. 1990) or during changes in stance width (Fung and Macpherson 1995). When an external load is applied to an animal's forequarters, limb verticality and trunk position are maintained while the horizontal projection of the COM shifts forward (Lacquaniti et al. 1990). Thus, the central control of kinematics based on body segment orientation is indicated.

In humans, upright posture involves vertical orientation of the trunk such that the body axis, a fictive line connecting the feet to the head (Mittelstaedt 1983), remains orthogonal to its base of support. Therefore, preservation of erect posture is dependent on control of trunk position and velocity since the upper body accounts for 2/3 of the total-body mass. Also, an internal representation of the trunk axis with respect to an external reference frame (i.e. gravity) is essential for the determination of head orientation and stabilization in space (Mergner et al. 1993). Since both the vestibular and visual systems reside in the head, maintenance of head stability, particularly during dynamic activity is paramount (Pozzo et al. 1995). However, head stabilization in space appears to be task specific whereas trunk stabilization is independent of task (Assaiante et al. 1997). Assaiante et al. (1977) examined angular displacement of the head, trunk and leg during single and double foot hopping. During flight, all subjects were found to stabilize the head and trunk in space while at landing, only trunk position was actively controlled. Thus, it was concluded that trunk stabilization in space was a primary controlled variable whereas head stabilization was dependent upon the postural task. In the central control of posture and movement, vertical trunk orientation has been suggested to have precedence over any other frame of reference (Berthoz 1991; Di Fabio and Emasithi 1997; Luyat et al. 1997). For example, Mouchnino et al. (1993) examined the relationship between final leg position and degree of trunk inclination during lateral leg lifting in trained dancers and naïve subjects. They found that dancers could accurately perform a leg lift to the desired 45° height with little trunk inclination whereas for naïve subjects trunk inclination and overestimation of the lift height (~ 56°) were highly correlated. These results led the researchers to conclude that for both groups of subjects, the trunk was used as a reference for determining leg position.

Head and trunk stabilization with respect to the vertical gravity axis has been shown to provide an egocentric reference value for posture and movement coordination in humans (Mergner et al. 1991; Mouchnino et al. 1993). It aids in focal target location and trajectory planning (Andersen et al. 1993; Hodges et al. 1999). During locomotion for example, vertical displacement of the head is minimized to promote gaze stabilization (Assaiante and Amblard 1993; Pozzo et al. 1990; Pozzo et al. 1995) while the trunk is stabilized in the frontal plane (Winter 1990). Baroni et al. (1999) have shown that during long-term exposure to microgravity, trunk orientation remains stable with little change over time whereas the location of the center of mass during stance is adjusted throughout the flight. Postural responses to activities such as voluntary leg lifting, demonstrate the dependence of balance on the direction of the gravity force vector (Mouchnino et al. 1993; Rogers and Pai 1990). Unlike the COM, there are sensory receptors in the trunk and legs that, in conjunction with vestibular input, may contribute to the calculation of the trunk orientation (Allum and Honegger 1998; Hlavacka et al. 1996; Maurer et al. 2000; Mittelstaedt 1998). Indeed, consistent measurements of forward trunk inclination recorded in microgravity and underwater provide evidence that proprioceptive graviceptors aid in the evaluation of vertical posture (Clement et al. 1988; Massion et al. 1995; Massion et al. 1997).

Active control of the trunk may be achieved through the coordinated displacement of one or more body segments. Mouchnino et al. (1992) found that during a lateral leg lift task, trained dancers were able to retain trunk verticality by means of pelvis rotation. The feedforward rotation was achieved through coupled movement at the ankle and hip joints. The control subjects were unable to maintain vertical trunk orientation despite specific instructions to do so. Covariation of the thigh and shank segments with respect to the vertical which minimizes trunk displacement has also been found to occur during locomotion (Borghese et al. 1996). Following externally triggered balance perturbations, central response strategies have been shown to involve coordination at the neck and hip joints so that trunk verticality can be regained as quickly as possible regardless of head position (Allum et al. 1997).

Since the postural reference frame is oriented with respect to the direction of gravitational forces, a primary factor in the maintenance of upright posture is the stabilization of the head in space (Amblard et al. 2001; Assaiante and Amblard 1996; Paillard 1991; Pozzo et al. 1989). Three important sensory input sources are supported by the head: the visual system, the vestibular system and neck muscle proprioceptors (see Section 1.2.2). Stabilization of the head in space is a well documented strategy for the control of posture following perturbation. From an early age (3-6 years) children are able to control head movement while walking on a stable surface (Assaiante and Amblard 1993). Amblard et al. (2001) examined the effects of weightlessness on head stabilization during lateral oscillatory trunk movement. Both with and without visual input, feedforward compensatory head adjustments were measured. Since head stabilization in space was maintained even though no equilibrium constraints were present, it was concluded that the head is used as a stable reference frame for the control of motion rather than the control of balance. In addition, the head contains the visual sensors and neck muscle afferents which convey information concerning the position of the head with respect to the trunk. Postural organization is based on head and/or gaze stabilization in space.

2.3 Postural responses due to internal and external perturbation

The ability to regulate posture and equilibrium in everyday situations is the result of combined predictive (anticipatory) and reactive (compensatory) balance control strategies (Horak et al. 1989; Maki and McIlroy 1997). Balance perturbations during standing can occur from forces that are anticipated, often internally generated, or from unexpected forces exerted by the environment. Successful balance recovery requires coordinated, fast and strong responses (Oddsson 1989).

2.3.1 Voluntary movements and anticipatory postural control

Any voluntary movement produces a postural perturbation because of the multi-linked nature of the human body. Forces are transmitted from the moving segment through joint connections to adjacent segments. Postural responses to voluntary movement are not limited movement of the focal segments, but are also accompanied by displacement of body segments not directly involved in the task (Massion 1992). Babinski (1899) has been credited as the first researcher to recognize that patients with "asynergie cerebulleuse" were unable to perform a forward trunk flexion without falling because they, unlike healthy subjects, lacked the compensatory displacement of the hip and knee. In 1943, (Hess) proposed a motor control model that included not one but two parallel processing systems. The first was responsible for the actual movement while the second managed the maintenance of equilibrium. This early work has been further extended by Massion and Mergner among others (Massion 1994; Mergner and Rosemeier 1998).

The idea that postural adjustments can occur in advance of voluntary movement was first introduced by Belenkii and colleagues (1967). By examining muscle activity during forward arm raises, they discovered that the muscles responsible for postural stability were activated prior to those producing the focal movement. These feedforward adjustments by the central nervous system have been termed "anticipatory posture adjustments" (APA) since they precede the onset of movement. APA provide a feedforward means by which the central nervous system can prevent or lessen upcoming disturbances to posture and equilibrium (Belenkii et al. 1967; Bouisset and Zattara 1987; Massion 1992; Vernazza-Martin et al. 1999). In addition, APA initiate any changes in body orientation that are required for movement production (Breniere and Do 1986; Rogers and Pai 1990). During single leg lifting in cats, a displacement of the COM towards the center of the triangle described by the remaining three support limbs has been found to occur before the lift (Birjukova et al. 1989). The COM displacement was initiated by activation of the triceps of the unloading forelimb which increases force under the limb. The thrust generated is believed to be used to shift the COM to the new stable position.

Several factors can affect APA generation: 1) the voluntary movement responsible for the perturbation, 2) the postural task and 3) the expected magnitude and direction of the upcoming perturbation. APA have been shown to scale according to the COM displacement needed to retain posture and equilibrium (Aruin and Latash 1995b, 1996; Mille and Mouchnino 1998; Toussaint et al. 1998). Slow voluntary movements are not very disruptive to posture and thus do not elicit APA responses (Crenna et al. 1987; Horak et al. 1984). Also, predictable externally triggered perturbations do not give rise to anticipatory responses while the same perturbation, when self triggered does (Aruin and Latash 1995b; Layne and Abraham 1991; Struppler et al. 1993). For example, the differences in postural response patterns between self-initiated versus experimenter-initiated unloading were examined by Aruin and Latash (1995b) Subjects were required to hold a balloon onto which a 2.2 kg weight was tied. The load was released either by a fast abduction at the shoulder by the subject, by popping the balloon by a tack taped to the subject's finger or by the experimenter popping the balloon. The results showed that APA were present during all subject-initiated unloading, but were absent when the unloading was triggered by the experimenter. In addition, when self-initiated, the magnitude of the APA scaled according to magnitude of the movement used to initiate the perturbation. Initial stance stability or configuration can also influence anticipatory responses (Couillandre et al. 2000; Do et al. 1991; Kaminski and Simpkins 2001; Nouillot et al. 2000; Shiratori and Latash 2000). During a front leg flexion task, Nouillot et al. (2000) observed APA when subjects started from a stable two-footed base. However, when the task was performed from single-limb support, APA were absent. Since APA facilitate movement production, in instances where large adjustments may create undo instability, APA are suppressed. APA associated with arm movements have been shown to be sensitive to perturbation direction (Aruin and Latash 1995a; Crenna and Frigo 1991). Aruin and Latash (1995a) found that fast forward arm flexion resulted in combined hip/ankle kinematic strategies, whereas fast arm extensions produced an ankle strategy. Also, forward and backward arm raising incurred higher magnitude anticipatory muscle responses than arm raising to the side and intermediate directions. Thus, to truly understand the motor control process, movements in multiple directions should be analyzed. In addition, APA can be developed through high level athletic training. Pedotti et al. (1989) compared the postural synergies generated by fast back extensions in trained gymnasts versus a control group. They found that the gymnasts produced a specific pattern of muscle activation that included an early firing of the gastrocnemius and hamstring that was missing in the controls. Calculation of a stability gauge confirmed that the postural strategy involving anticipatory muscle response improved performance in the highly trained athletes.

With respect to voluntary movement, postural control strategies and their associated APA have been studied most often in quasi-static tasks involving displacement of the upper body such as axial bending or arm raising (Table 1.1). Few researchers have examined response parameters in relation to tasks which involve displacement of segments that are directly involved in body support such as gait initiation since voluntary movements of this type necessitate postural changes in order to optimize performance as well as to maintain balance (Birjukova et al. 1989; Breniere and Do 1986; Cordo and Nashner 1982; Layne and Abraham 1991).

	TASK	STUDY	REFERENCE
Upper limb	Jaw opening/closing	Adults	(Torisu et al. 2002)
	Shoulder flexions	Adults – w/wo load	(Bouisset et al. 2000b)
		Adults – variable velocity w/wo load	(Bouisset et al. 2000a)
		Adults – variable stance	(Fujiwara et al. 2003)
		Children – 3-10 yrs, w/wo load	(Hay and Redon 2001)
		Adults – ankle vibration	(Kasai et al. 2002)
		Adults – pistol shooting	(Minvielle and Audiffren 2000)
		Adults	(Patla et al. 2002)
		Theoretical model	(Pozzo et al. 2001)
		Adults – unstable support	(Shiratori and Latash 2000)
		Adults w/wo light touch or hand support	(Slijper and Latash 2000)
		Adults – w/wo muscle fatigue	(Vuillerme et al. 2002)
	Unloading	Adults – hemiparetic patients	(Slijper et al. 2002b)
		Adults – variable speed	(Slijper et al. 2002a)
	Grip	Adults – variable gravity vector	(Nowak et al. 2002)
		Adults – variable load	(Winstein et al. 2000)
	Wrist flexion	Adults – w/wo elbow support	(Chabran et al. 2001)
	Lifting	Adults – variable load	(Commissaris et al. 2001)
		Adults – variable load	(Heiss et al. 2001)
		Children – 5-8 yrs	(Schmitz and Assaiante 2002)
	Push and Pull	Adults – unstable support	(Dietz et al. 2000)
		Adults – Alzheimer's and Parkinson's patients	(Elble and Leffler 2000)
		Adults – sitting	(Le Bozec et al. 2001)
	Pointing & reaching	Stroke patients	(Fisher et al. 2000)
		Children – developmental coordination disorder	(Johnston et al. 2002)
		Varied stance	(Kaminski and Simpkins 2001)
		Adults – variable posture	(Teyssedre et al. 2000)
	Catching	Adults – load unload	(Aruin et al. 2001b)
		Adults – catching and fast arm raises	(Aruin et al. 2001a)
		Adults	(Loram and Lakie 2002)
		Adults	(Shiratori and Latash 2001)
	Trunk bending	Adults	(Alexandrov et al. 2001)
Lower limb	Lower limb flexion	Adults	(Nouillot et al. 2000)
	Vertical jump	Adults	(Le Pellec and Maton 2000)
		Adults	(Le Pellec and Maton 2002)
		Adults – toe-rise	(Adkin et al. 2002)
	Gait initiation	Children – 1-5 yrs	(Assaiante et al. 2000)
		Adults – reduced support	(Couillandre et al. 2000)
		Adults – reduced support	(Couillandre et al. 2002)
		Children – 4-6 yrs	(Malouin and Richards 2000)
		Adults – bilateral vestibular loss patients	(Sasaki et al. 2001)
		Adults – cerebellar patients	(Timmann and Horak 2001)
	Compensatory stepping	Adults	(Liu et al. 2003)
		Adults – variable perturbation	(Zettel et al. 2002)

Table 2.1 Voluntary movement studies examining anticipatory postural responses from the year 2000 to 2003

2.3.2 Unexpected perturbations and triggered postural responses

Postural reactions in response to external perturbations are essential for regaining equilibrium. The central nervous system must quickly convert and regulate sensory feedback into appropriate balance responses to avoid falls. Late into the 19th century, thanks to the ataxiagraph, scientists first began measuring human postural sway (Hinsdale 1887). By 1938, force-plate devices were developed to explore balance during quiet stance (Hellebrandt 1938). But, it was not until Nashner's introduction of a moving balance platform that a tool became available to study the effects of external perturbation on balance (Nashner 1976). Studies using support surface displacement have shown that when balance is suddenly disrupted, a task specific set of strategies are employed by the central nervous system to control posture and regain equilibrium (Allum and Honegger 1992; Dietz et al. 1993; Schieppati et al. 1995). Postural control strategies triggered by surface perturbations can be divided into two types: fixed-support and change-in-support. Change-in-support strategies involve either stepping or grasping a support in order to regain equilibrium and, when given a choice, represent the preferred means by which subjects regain balance after external perturbation (Maki and McIlroy 1997). Fixed-support-strategies, on the other hand, require movements of the arms and/or legs to be restrained either voluntarily or fixedly. This paradigm enables the evaluation of center of mass control over an unchanging base of support (Horak and Nashner 1986).

The choice of strategy is dependent upon: 1) the available sensory information, 2) the type of perturbation, 3) the support surface characteristics, 4) individual biomechanics and 5) the constraints defined by the task. Buchanan and Horak (1999) examined the effects of sinusoidal surface translation of varying speed on postural response in healthy subjects. They found that at slow frequencies, subjects simply rode the platform, however, as the translation frequency increased, the subjects stabilized the head and trunk in space. With the eyes closed, head and trunk control was compromised. In addition, joint motion changed from an ankle strategy to a hip-ankle combined strategy in which COP amplitude was increased while the magnitude of COM displacement was reduced. Both the type of perturbation and the availability of sensory impact had an impact on postural response. Biomechanical changes due to aging have been shown to correspond to changes in reactive balance strategy (Allum et al. 2002). When presented with multidirectional surface rotations during standing, older adults (60-75 years) demonstrated an increased trunk roll plane stiffness that was not found in younger subjects (20-34 and 35-55 years). Since early compensatory trunk movements were restricted, theoretically trunk displacement in the direction of the perturbation should lead to a fall. However, reactive arm movements were also observed in the older group of subjects. It was concluded that because of the effects of aging, older individuals have developed new strategies for coping with unexpected perturbations to balance.

The organization of triggered postural responses has been shown to be direction dependent. Henry et al. (1998a; 1998b) have demonstrated that multi-directional surface translations produce control strategies that focus primarily on control of ankle torque in the sagittal plane and hip torque in the frontal plane. Perturbation in the intermediary directions resulted in a coupled hip-ankle response, as has been previously described by Winter et al. (1996). The directional sensitivity was believed to be due to biomechanical constraints.

In real life, threats to balance are not only multi-directional, but multi-dimensional. Until recently, rotations of the support surface, as opposed to translations, had been predominately limited to displacement in the pitch plane, i.e. toes-up or toes-down (Diener and Dichgans 1988; Diener et al. 1988; Gurfinkel et al. 1995; Nashner 1977). However, more recently, Carpenter et al. (1999) have reported on a series of experiments in which the postural control strategies associated with multi-directional, constant amplitude surface rotations were examined. They discovered a directionally sensitive trunk afferent triggered response pattern. However, these results are limited in their design in that the subjects' ankles were secured to the moving platform and their arms were held tight against their body. With the ankle thus immobilized and arm movement minimized, it is probable that some muscle activity and joint movement was inhibited. Free standing guarantees that triggered postural responses will more closely mimic those found in real life situations.

2.4 Effects of training on balance

The skillful execution of a motor task or recovery following a moment of unexpected instability involves implicit internal knowledge of both personal biomechanical and equilibrium limitations. Training improves performance by shifting control from a feedback system with an overabundance of possible strategies to one in which performance parameters are "predicted in the central control of the motor act" (Massion 1992). In other words, the number of potential solutions (degrees of freedom) is reduced which in turn decreases the latency of postural response to either internal or external perturbation. Thus the destabilizing effects of the perturbation are reduced. Feedback input can then be used for fine-tuning performance quality rather than gross postural adjustment.

Training has been shown to positively impact proactive and reactive postural responses in groups as far ranging as the very young or the very old. In infants, these positive effects have been demonstrated during both sitting and standing tasks (Hadders-Algra et al. 1996; Sveistrup and Woollacott 1997). For example, Sveistrup and Woollacott (1997) examined the results of experience on performace of a stand and balance task in infants following forward and backward translations of the support surface, as determined by muscle function. The infants were divided into two groups. Both groups were tested twice at an interval of five days. On the three days between testing, one group was trained on the moving platform while the other simply visited the laboratory. EMG analysis revealed that the surface perturbation showed a higher probability of generating a functionaly appropriate muscle response in the trained infants as compared to the untrained group. No differences were found in terms of muscle onset latencies or number of trials exhibiting agonist-antagonist coactivation. Therefore, the researchers concluded that, during development, familiarity with a postural task can induce specific changes to the automatic postural responses. In the elderly, balance performance has also been shown to improve following practice (Hu and Woollacott 1994a, 1994b; Mynark et al. 2002). Hu and Woollacott (1994a, 1994b) characterized the postural responses used by older subjects (65-90 years) to maintain double- and single-limb stance before and after a ten-hour multisensory balance training program. The trained subjects demonstrated improved stability during stance which was still present when the same subjects were retested 4 weeks later. It was concluded that multisensory balance training improves postural stability in older persons.

The specificity of training and its applicability to different functional goals has been addressed by a number of researchers. For example, consider the study presented by Young and Marteniuk (1998) in which subjects were presented with a multi-joint kicking task for which they completed 16 blocks of 16 trials. The researchers were interested in assessing motor learning. Specifically, whether once a movement has been learned is there further adaptation to the control patterns with practice. They determined that once subjects learned the task, a particular motor pattern was systematically chosen. Furthermore, with practice, variation between trials was reduced. Eloranta (2003) examined the effect of specific sports training on jumping ability. Five different groups of athletes participated in the study: soccer players, swimmers, high jumpers, and poor and good vertical jumpers. EMG analysis revealed that each athletic group behaved differently with the swimmers and soccer players demonstrating the poorest performance.

It was concluded that sports training leads to adaptive changes in automatic programming that appear during motor activities outside of the trained discipline. Along those lines, Marin et al. (1999) have shown that, beyond just modifying response, long-term training places a constraint on motor behavior. Gymnasts and non-gymnasts were instructed to maintain stance either on the floor or on a narrow beam while following an oscillating target with their eyes and head. Depending upon the target movement frequency, either an ankle or hip strategy was observed. The transition time between the coordination strategies was later for the gymnasts than the non-gymnasts regardless of the support condition. Since in competition gymnasts are penalized for hip movement, it was concluded that training has enabled gymnasts to adapt their control strategies to meet the particular requirements of their athletic discipline.

Classical ballet, like gymnastics, is an athletic endeavor which focuses on balance skills. Also, classical technique places strict rules on the performance of those skills. In particular, vertical trunk stabilization is stressed. Therefore, it is reasonable to expect that training in classical ballet should lead to overall better balance performance. However, it is difficult to make such a bold statement since there is very little quantitative data in the literature which describes how dancers perform their highly trained movements and even less in which dancers are compared to non-dancers. For instance, conflicting results regarding dancers' reliance on vision for postural control have been reported. On the one hand, Golomer et al. (1999) and Mesure et al. (1997) have demonstrated that dancers are better able to maintain balance without vision during static or dynamic balance tasks. However, both Hugel et al. (1999) and Perrin et al. (2002) found that dancers performed better than non-dancers only when vision was present. The issue of visual versus proprioceptive dominance during stance, at least for dancers, is not resolved. In an important work concerning the balance abilities of dancers, Mouchnino et al. (1992) have found that dancers employ a unique postural strategy when asked to perform a lateral leg lift. The dancer strategy involved maintenance of trunk verticality throughout the movement. Center of mass displacement was managed through feedforward rotation of the pelvis and inclination of the stance limb. Non-dancers, on the other hand used counter-rotation of the trunk which was temporally coupled with movement onset. However, this study was limited by its methodological constraints. First, kinematic analyses were only performed in the frontal plane. Since humans are capable of three-dimensional movement, a true model of kinematic activity can not generated by joint displacements along a single plane. Second, the direction of the focal leg lift was restricted to side lifting. However, postural response is affected by perturbation direction (Aruin and Latash 1995a; Carpenter et al. 1999; Henry et al. 1998b). Also, arm movement was restrained by folding them across the back which in turn affects COM positioning. Therefore, to better understand the effects of dance training on postural performance, multi-directional movement should be analyzed in a three-dimensional environment.

2.5 Qualitative and quantitative analyses of coordinated behavior

A number of different techniques have been employed to describe the complexity of human movement and balance control. These range in sophistication from simple descriptive analyses to more advanced statistical methods. The selection of analysis tool is dependent upon the goals of the study.

Descriptive methods have been used to compare movement performance between individuals or group of individuals. These may include analysis of peak-to-peak angular joint displacements, COM/COP displacement or event timing etc. Typically each variable of interest is analyzed separately. The results are then used to describe the targeted activity.

Levels of coordination have been assessed by means of angle-angle diagrams (Charteris 1982; de Bruin et al. 1982). The purpose of these diagrams is the identification of spatial and temporal relationships between body segments. Time is embedded with the plot and is not illustrated separately. Both cyclical and discrete movements can be described. Because of the nature of the comparison, angle-angle diagrams are restricted to two-dimensional analysis of two variables.

Phase plane portraits are a qualitative measure that explores the dynamics associated with coordinated movement. Typically movement of one joint is plotted against a movement parameter such as velocity or acceleration. Phase plane portraits enable the identification of "signature" behaviors which can be used to characterize certain pathologies (Hurmuzlu et al. 1994; Hurmuzlu et al. 1996). Again, these analyses are limited to two dimensions.

The visualization methods presented thus far are valuable tools however they do not provide a complete behavioral picture. Therefore, multivariate analysis techniques have been used. One of the most popular is principal component analysis (PCA). PCA is a classical statistical technique used to uncover subsets within a group of interrelated variables. The goal of PCA is to identify "hidden" factors which reside within a set of measured variables. These factors can then be given meaning based on the measured variables which most contribute to their creation. PCA is commonly used for pattern recognition, data reduction, and hypothesis testing. It can provide a functional representation of a complex data set.

A principal component is defined as a linear combination of the maximal variance in the data set such that each successive principal component is orthogonal (and therefore uncorrelated) to the previous principal component of the same data set:

$$R = USV', \tag{2.6}$$

where R = mean centered covariance matrix, U = column space of the variable matrix which corresponds to the eigenvectors, V = unit vectors pointing in the same direction as the principal components which are equivalent to the normalized time variability of the factors and, S = diagonal matrix (XX′). The factors generated are representative of the underlying processes that have created the correlations among the variables. Disadvantages of PCA include sensitivity to outliers, missing data and poor correlations between the variables. Therefore, care must be taken in data selection and preprocessing.

PCA is a useful tool for extracting coordinated patterns of kinematic, kinetic or EMG activity. In the field of motor control, it has been predominately used to elucidate patterns in muscle activation for tasks ranging from upper trunk bending (Lariviere et al.

2000), treadmill locomotion (Merkle et al. 1998), swimming (Rouard and Billat 1990) and overground walking (Patla et al. 1985). Evidence of central nervous system coding of muscle activation patterns was revealed by PCA performed on EMG activity of eight muscles spanning the elbow joint during submaximal isometric contraction (Kutch and Buchanan 2001). More than 98% of the variance in the data set could be described by the first two eigenvectors. After scaling and shifting the PCA data, the first principal component was found to correspond to the measured elbow joint torque while the second component represented the sum of the eight normalized EMG signals.

PCA has also been used to describe patterns of ground reaction forces during a sit-to-stand task (Borzelli et al. 1999). The ground reaction forces under the feet were measured for 82 people during 5 sit-to-stand movements for a total of 410 trials. PCA performed on the data revealed that the first two components effectively described 90% of the total data variance. Furthermore, the first principal component did not vary from subject to subject whereas the second component demonstrated a repeatable pattern only within an individual subject. Therefore, it was concluded that the first component was related to the motor task and the second was related to individual control parameters.

2.6 Conclusion

In conclusion, the control of upright balance is a constant challenge for human beings due in part to the multi-segmental nature of the human body. However, the central nervous system is able to reduce the number of degrees of freedom through the employment of postural strategies. Two different components contribute to the control of balance and equilibrium: one which is based on feedback from sensory information and another which is generated from a central set of response patterns. The selection of a strategy is dependent upon the postural goal associated with the task. Athletic training, among other things, has been shown to influence the choice of strategy used during voluntary movement and produce modifications to the automatic responses evoked by unexpected perturbations. Multivariate analysis techniques such as principal component analysis are data visualization tools which can facilitate the characterization of postural strategies through data reduction and pattern recognition. Combining the output from this tool with those from traditional analysis methods provides further insight into the central control of balance and equilibrium.

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Chapter 3 Postural responses triggered by multi-directional leg lifts and surface tilts

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Submitted to: Experimental Brain Research May 2003

The ability to regulate postural orientation and equilibrium in everyday situations is the result of combined predictive (anticipatory) and reactive (compensatory) balance control strategies (Horak et al. 1989; Maki and McIlroy 1997). Balance perturbations during standing can occur from forces that are expected, often internally generated, or from unexpected forces exerted by the environment. Anticipatory postural adjustments (APA) precede voluntary movement and provide a feedforward means by which the central nervous system can prevent or lessen any destabilizing effects that an upcoming movement will have on posture and equilibrium (Belenkii et al. 1967; Bouisset and Zattara 1987; Massion 1992). On the other hand, when balance is unexpectedly disturbed, the central nervous system must quickly convert and regulate sensory feedback into appropriate balance responses, triggered postural responses (TPR), to avoid falls. My hypothesis is that, given the same postural task such as weight shifting from double to single limb support, a common control strategy is used to prevent instability whether the perturbation is generated internally (APA) or externally (TPR). The results of this study will provide important information concerning the central control of posture. In addition, these results may have implications for the rehabilitation of individuals with impaired balance. If our hypothesis is true, and a common control variable weighting is found in similar voluntary versus triggered postural tasks, then the practice of specific movements may be used to improve balance in real life situations.

3.1 Abstract

The aim of the present study was to investigate the relationship between anticipatory and reactive components of postural control. We contrasted the kinematic, kinetic and EMG responses to multidirectional voluntary leg lifts with those elicited by unexpected surface tilts. We hypothesized that following either a voluntary or forced weight shift from double to single limb support, a common strategy would exist to control displacement of the center of pressure under the feet and to stabilize the head and trunk. Nine young female subjects stood with a standing posture of 45° toe-out and their arms abducted to shoulder level. On the experimenter's signal, subjects either (1) lifted one leg as fast as possible in one of ten directions (R/L front, R/L side, R/L back, R/L diag front, R/L diag back) to a height of 45° or (2) maintained standing as the support surface tilted at a rate of 53°/s to a height of 10° in one of eight directions (toes-up, R/L-up, toes-down, R/L diag toes-up, R/L diag toes-down). For both tasks, our results showed that the center of pressure (COP) displacement began before or in conjunction with displacement of the center of mass (COM) after which the COP oscillated about the horizontal projection of the COM. In addition, the muscles were recruited in a distal-to-proximal sequence, either in anticipation of the voluntary leg lift or in response to the sudden surface tilt. Thus, the COP was being used dynamically to control displacement of the COM. Head, trunk and pelvis movement was quantified by means of principal component analysis (PCA). More than 95% of the variance in the data could be described by the first two eigenvectors. PCA revealed specific coordination patterns which were dominated by pelvis rotation in one direction and head/trunk rotation in the opposite

direction. Unexpected surface tilting elicited an automatic response strategy which focused on control of the orientation of the head and trunk with respect to the vertical gravity vector while trunk verticality was compromised for movement generation and the recovery of postural equilibrium during leg lifting. In conclusion, when subjects are exposed during quiet stance to postural perturbation that involves a sudden unloading of one foot, the primary postural goal whether the task is self-initiated or unexpected, is control of the body's COM position through trunk stabilization and the appropriate shift of the center of pressure under the feet.

3.2 Introduction

The ability to regulate postural orientation and equilibrium in everyday situations is the result of combined anticipatory and reactive balance control strategies (Belenkii et al. 1967; Bouisset and Zattara 1987; Horak et al. 1989; Maki and McIlroy 1997; Massion 1992). Balance perturbations during standing can occur from forces that are anticipated, often internally generated, or from unexpected forces exerted by the environment. Successful balance recovery requires coordinated, fast and appropriate responses.

The organization of both anticipatory and automatic postural responses has been shown to be direction dependent. Aruin and Latash (1995) have shown that the anticipatory postural adjustments found during multi-directional fast arm raising vary depending upon the direction of the lift. Directionally dependent kinematics and muscle responses have also been found in response to multi-directional surface translations (Henry et al. 1998a, b) and surface rotations (Carpenter et al. 1999). Since real life threats to balance are not limited to a single geometric plane, the effects of multi-directional perturbation need to be addressed to truly understand the ramifications of postural instability on CNS control.

The purpose of any postural adjustment during upright stance, whether anticipatory or reactive, is the maintenance of equilibrium. In the case of anticipatory adjustments, balance is achieved at the expense of postural orientation whereas automatic responses involve changes in segmental orientation to regain posture (Massion 1992). In either case, it is necessary to minimize displacement of the body's center of mass (COM) to avoid instability (Winter et al. 1990). However, the means by which the CNS selects a control strategy from the over abundant number of possible solutions, as well as the organization of the central control, are not well understood. In particular, very little is known concerning the relationship between anticipatory and reactive response strategies. Two theories have been proposed concerning the control of coordinated movement. The first suggests that a single central control is responsible for the entire action (Bouisset and Zattara 1987), while the second divides control between the movement performance and the maintenance of equilibrium (Massion 1992). The choice of postural strategy has been shown to be driven by task and context in that the selection and hierarchical ordering of control variables can change depending upon task goals (Le Pellec and Maton 1999), environmental conditions (Reschke et al. 1998; Shiratori and Latash 2000) and individual biomechanical constraints (Kolb and Fischer 1994). In the maintenance of quiet stance, anticipatory and automatic responses have the same overall goal of controlling equilibrium. One important question is, given the same postural task, whether the controlled variables selected by the CNS the same during self-initiated movement as those elicited by unexpected perturbation? Another question is whether there are differences in the organization of the central control.

We hypothesize that following either a voluntary or forced weight shift from double to single limb support, similarities exist in the postural control strategies. In particular, two primary variables are actively controlled by the CNS, head and trunk stabilization and displacement of the center of pressure under the feet. Evidence for CNS control of vertical head and trunk orientation has been found during locomotion (Assaiante and Amblard 1993; Pozzo et al. 1990; Winter et al. 1990) and lateral leg lifting (Mouchnino et al. 1992). Since in humans, the upper body accounts for approximately two-thirds of the total mass, tasks involving the preservation of erect posture depend upon control of trunk position and velocity. During stance, if vertical head and trunk orientation are maintained, regulation of COM positioning can be achieved through foot contact with the support surface. Therefore, to evaluate CNS control of these two variables, we compared three-dimensional kinematic and kinetic as well as muscle responses to expected, internally generated versus unexpected, externally triggered weight shifts that occur during multi-directional voluntary fast leg lifts and sudden surface tilts.

3.3 Methods

3.3.1 Subjects

A convenience sample of nine active young women (mean age 26 ± 7.1) with no history of neurological or musculoskeletal problems were recruited for this study. Their height and weight ranged from 154.7 to 169.8 cm and 41.94 to 60.61 kg respectively. All subjects participated in some level of physical activity from karate to basketball. All subjects gave their informed consent to the experimental protocol previously approved by the institutional ethics committee.

3.3.2 Procedure

Two experimental protocols were performed: voluntary leg lifts and unexpected surface tilts. The initial stance position was the same for both experiments: barefoot, weight evenly distributed across both feet, with heels touching and oriented in a 45° toe-out position. Each foot was placed on an individual force plate (AMTI OR6-7). Arms were abducted to shoulder height (see figure 3.1A). Subjects were instructed to maintain this initial posture. All experiments were conducted in a single day to ensure that within-subject comparisons could be made. Subjects were given a practice session prior to recording.

Experiment 1: Following an audio signal, subjects were required to lift either their right or left leg in one of five directions (front, side, back, front 45° diagonal, or back 45° diagonal, figure 3.1B) to a height corresponding to an inter-leg separation angle of 45°. Subjects were instructed to perform the movement as fast as possible, with no knee flexion and maintain the final leg position for a minimum of 3 seconds. The choice of swing leg and lift direction were randomized within test blocks (i.e. one lift in each of the ten directions). Subjects completed five test blocks for a total of 50 trials.

Experiment 2: Upon the experimenter's trigger, the support surface was tilted in the pitch and roll planes. The support surface was mounted over a six degree-of-freedom motion base servo controlled by six electro-hydraulic actuators (Fung and Johnstone 1998). Ten degrees of ramp-and-hold surface tilt in one of eight random axial directions (right side-up, left side-up, toes-up, toes-down, toes-up 45° diagonal and toes-down 45° diagonal) was presented at a peak velocity of 53°/s (figure 3.1B). The tilt magnitude and speed were sufficient enough to cause a shift from the initial two-footed stance to a single limb. Two catch trials with no surface tilt were included to reduce subject anticipation of upcoming perturbation direction. Tilt direction was randomized within test bocks (i.e. one tilt in each of the ten directions). Subjects completed five test blocks for a total of 50 trials.

3.3.3 Data recording

A six-camera VICON 512 system (Oxford Metrics Ltd.) was used to capture three-dimensional position data at 120 Hz from 35 retro-reflective markers placed over anatomical landmarks (figure 3.1A). In addition, four markers were placed along two orthogonal axes of the movable platform. A biomechanical model (Plug In Gait, Oxford Metrics Ltd.) was used in conjunction with kinematic data and anthropometric measures (height, weight, leg length and joint widths) to define body segments, joint angles and calculate total body centre of mass.

Ground reaction forces and moments were acquired at 1080 Hz by two adjacent AMTI OR6-7 force plates embedded within the support surface. Resultant center of pressure (COP) x and y vectors were calculated as the weighted sums from the individual signals as described previously (Henry et al. 1998a). Inertial components in forces and COP data were corrected due to movement of the support surface (Preuss and Fung 2003).

Four lower limb and trunk agonist-antagonist muscle pairs on each subject's right side were instrumented with bipolar Ag-AgCl disposable surface electrodes (Blue Sensor): tibialis anterior (TA), gastrocnemius medialis (MG), rectus femoris (RF), semitendinosus (ST), tensor fascia laeta (TFL), adductor (AD), rectus abdominus (RA) and erector spinae at L_3 level (ES) to record electromyographic (EMG) signals using an 8-channel TELEMG system (BTS). EMG signals were amplified, digitized, and transmitted to the remote amplifier via optical fibers. These signals were band-pass filtered (10-400 Hz low-pass) and sampled at 1080 Hz. EMG signals were further full-wave rectified and low-pass filtered at 100 Hz during off-line analysis.

3.3.4 Data analysis

All data were time adjusted to movement onset. Movement onset was defined as the time at which the difference between the vertical velocity of the malleolus marker (exp. 1) or platform markers (exp. 2) and the mean background velocity values was equal to or greater than twice the standard deviation (95%) (Mouchnino et al. 1992). For experiment 1, an anticipatory phase and a maintenance phase were also designated. The start of the anticipatory phase was indicated by the first change in the lateral velocity of the COP equal to or greater than the mean background plus twice the standard deviation (Mouchnino et al. 1992). The maintenance phase was set as the 1000 ms period after which the vertical velocity of the malleolus marker slowed to 0±5% of its maximum. Because of the electromechanical delay between muscle firing and force generation, each phase was shifted 30 ms earlier for EMG analysis. An example of these time divisions for a single subject can be seen in figure 3.2A. The data from experiment 2 were subdivided into three predetermined time intervals for analysis: 0 to 100 ms from stimulus onset, short-latency reflex period; 100 to 225 ms, balance correction phase I; 225 to 350 ms, balance correction phase II; 350 to 700 ms, stabilizing phase. For EMG analysis, the stretch reflex phase was shortened by 30 ms to end at 70 ms. The subsequent time intervals retained the same length, but began 30 ms earlier. An example is shown in figure 3.2B.

Three-dimensional kinematic analysis was carried out on the head, trunk and pelvis segments. The global head angle was taken as the angle between the center of the four head markers and the vertical gravity vector. Trunk inclination was taken as the angle between the trunk axis and the vertical axis. The pelvis was modeled as a plane which contained the two posterior- and two anterior- superior iliac spine markers. The pelvis angle was taken as the angle between the pelvis and the vertical axis. Total angular excursion for each variable was calculated. Data from different trials of each individual were ensemble-averaged across each direction. These averages were then pooled to produce a population average for each direction.

In addition, segmental coordination patterns of the head, trunk and pelvis were evaluated in the sagittal, frontal and horizontal planes by means of principal component analysis (PCA). For each trial of each subject a covariance matrix **R**, containing the mean centered time-varying angular displacements of the planar variables, was computed. PCA was used to determine the three rank-ordered eigenvectors, $u_1 - u_3$ and associated scores of **R** that correspond to the orthogonal directions of maximum variance in the data set. To further improve separation between variables with intermediate versus very large or very small loadings, a Varimax rotation was performed (Merkle et al. 1998). Thus, all the axes in the data set were mathematically rotated such that the first new axis corresponds to the direction of the greatest variance in the data. Each successive axis represents the maximum residual variance. Coordination patterns were then assessed by using the first two eigenvectors, u_1 and u_2 to define a plane of angular covariation. The third eigenvector, u_3, was used to determine the orientation of the plane in the data space. A similar method has previously been employed for the analysis of foot, shank and thigh segment orientations during locomotion (Bianchi et al. 1998; Borghese et al. 1996; Grasso et al. 2000). The "fit" of the plane was evaluated by the proportion of the variance described by the first two eigenvectors.

Muscle latencies were determined manually as the first burst which exceeded a threshold of two standard deviations above the background signal, lasting at least 25 ms. A muscle had to be recruited at least 3 out of 5 trials to be considered to contribute to dynamic postural response. The mean integral of each muscle response was determined by integrating the area under the EMG response curve for each time segment of interest after filtering the data at 10 Hz (see figure 3.2). The mean background was subtracted. The data were then normalized to the maximum response for each muscle regardless of perturbation direction or type of perturbation. Lastly, the integrals from each subject, for each direction were averaged so that an ensemble group profile could be determined. Since each subject was instrumented for EMG only on their right side, all data from right leg lifts and right side up/right diagonal up surface tilts were termed "unloaded limb" while left leg lifts and left side up/left diagonal up surface tilt data were "loaded limb".

Comparisons between voluntary and automatic responses were made using a repeated-measure two-way analysis of variance (ANOVA), the independent variables being task (voluntary leg lifts versus unexpected surface tilts) and direction of perturbation (see figure 3.1B). A p-value of 0.05 was accepted to be significant in determining the main and interaction effects, after adjusting with the Bonferroni test. Pairwise comparisons were made with Tukey's tests. All statistical analyses were performed with the aid of the statistical software package Statistica (StatSoft Inc.).

3.4 Results

3.4.1 COP and COM

Figure 3.3A shows the relation between peak COP/COM excursions and leg lift (left column) or surface tilt (right column) direction. During voluntary leg lifts, neither medial-lateral COP nor COM peak excursion showed any statistical significance with regards to lift direction. However, anterior-posterior displacement of the COM during front and front diagonal leg lifts resulted in peak displacements of 45-55 mm while peak values for the other directions averaged only 20-35 mm. By contrast, during surface tilts both COM and COP peak displacements were sensitive to perturbation direction. Anterior-posterior movement of the COM and COP was largest during toes-down and toes-down diagonal tilts (225°, 270° and 315°) at 20 mm and 30 mm respectively. On the other hand, medial-lateral displacements were largest during pure roll rotations (0° and 180°) with peak excursions of 35-40 mm for the COM and 130-140 mm for the COP as compared to values of 5 mm and 20 mm for pitch rotations (90° and 270°).

Figure 3.3B presents the horizontal projection (average of 5 trials from nine subjects) of COP and COM for both the voluntary (left column) and triggered (right column) tasks from each of the five right-sided perturbations. For all directions, COP during the leg lift task was predominately characterized by lateral displacement. As expected, an anticipatory lateral shift away from the support side which averaged 96 ±5.5 mm in magnitude was found. Onset of the lateral displacement occurred between 283 ±115.1 ms (R side lift, 0°) and 365 ±93.6 ms (L diagonal back, 270L°) before movement began. Forward leg lifts also produced a slight forward anticipatory adjustment. During the movement phase, there was a large and backward COP shift in the direction of the support leg (220 ±9.8 mm). In addition, there was a relatively slow posterior COP displacement followed by a quick shift forward. The maintenance phase included anterior-posterior oscillation and a small reverse lateral shift. COP response following surface tilts, unlike the voluntary task, was direction specific. COP excursion began in the direction of the perturbation (unloaded limb, see figure 3.1B). Then, during the balance correction phase, the COP made a linear shift reversal away from the unloaded limb. COP displacement during the stabilization period included a return towards the neutral start position.

During the voluntary movement, anterior-posterior COM displacement followed a direction-specific path. Movement in forward directions resulted in a forward displacement, while movement in backwards directions led to a small forward shift, approximately 10 mm, followed by backwards displacement as the leg was lifted. Unlike the COP, the COM continued to move laterally in the direction of the support leg during the position maintenance phase to reach a displaced position near that of the COP. Following the unexpected surface tilts, the COM excursion pathway moved away from the stimulus direction towards the loading side. In summary, a toes-up rotation (90°) resulted in a backwards shift whereas a toes-down rotation (270°) led to a forward shift. Interestingly, toes-down rotations resulted in a 50% larger overall COM displacement than toes-up rotations (12 ±9.4 mm versus 23 ±4.5 mm).

3.4.2 Head, trunk and pelvis

Head, trunk and pelvis angular excursions for the sagittal, frontal and horizontal planes are shown in figures 3.4A and 3.5A, respectively. These examples are from a left diagonal front leg lift and left diagonal toes-up tilt from a single subject. The kinematic response to diagonal perturbations, whether triggered by voluntary leg lifts or unexpected surface tilts, was a combination of the corresponding orthogonal responses (e.g. front/side, toes-up/side-up, back/side or toes-down/side-up). In general, the head, trunk and pelvis followed a set excursion path based on perturbation direction.

As shown in figure 3.4A, during leg lifting, pelvis displacement was larger than that of either the trunk or head and was exemplified by rotation away from the lifting leg in the sagittal and frontal planes and towards the lifting leg in the horizontal plane. As expected, maximal excursions were seen during front/back leg lifts in the sagittal plane (~15-25°) and lateral/diagonal lifts in the frontal plane (~25°). Head and trunk displacements were smaller (~5° and ~10°) and involved a scheme similar to that of the pelvis. The only exception was trunk movement in the sagittal plane during back leg lifts where the trunk rotated back towards the lifting leg. During unexpected surface tilts, as illustrated in figure 3.5A, pelvis displacement was larger than that of the head or trunk only in the frontal and horizontal planes. Interestingly, trunk and pelvis movement in the frontal and horizontal planes involved rotation of the two segments in opposition. The pelvis tilted towards the support limb in the frontal plane, while the trunk and head tilted towards the swing limb. In the horizontal plane, the pelvis rotated towards the swing limb while the head and trunk moved in the opposite direction. Maximal displacements were found during toes-down/diagonal tilts in the sagittal plane (~5°) and side/diagonal tilts in the frontal and horizontal planes (~3-8°).

These observations were quantified by computing the principal components of the angles for each plane. These principal components are a linear combination of the variance in the data such that each component is statistically independent of one another and describes decreasing smaller amounts of the variance. Tables 3.1 and 3.2 report the percent of variance described by the three eigenvectors, $u_1 - u_3$. In all three planes, for all subjects, in all perturbation directions, the first two eigenvectors describe more than 95% of the variance. In most cases, that number is closer to 98%. Thus, the planar model is justified. Figures 3.4B and 3.5B show the variable "loadings" for the first two eigenvectors for each perturbation direction in each plane, while figures 3.4C and 3.5C illustrate average scores for a left diagonal front leg lift or a left diagonal toes-up surface tilt.

Regardless of perturbation direction, the first principal component of the leg lifting data began on or slightly before movement onset and plateaued around the start of the maintenance phase (figure 3.4C). Angular displacement in both the sagittal and frontal planes was dominated by pelvis rotation. In the sagittal plane, front leg lifts resulted in backwards tilts while the pelvis tilted forward during back and lateral leg lifts. The pelvis tilted up in conjunction with the lifting leg in the frontal plane. Backwards leg lifts (i.e. 225°, 270°, and 315°; see figure 3.1B) also involved some trunk displacement in the same direction as the pelvis in the frontal plane and in opposition in the sagittal (figure 3.4B). The second principal component began after the first component and generally finished by the onset of the maintenance phase. In the sagittal and frontal planes, the trunk was responsible for most of the second eigenvector. The displacement pattern was similar to that of the pelvis in the first component. The head was relatively stable in the sagittal plane and accompanies the trunk in the frontal plane. Analysis of peak-to-peak displacements found that trunk displacement patterns with respect to perturbation direction were similar to those of the pelvis albeit one-third the magnitude.

In response to platform rotation, pelvis displacement was small in the sagittal plane with overall head movement greater in all directions. Examination of the first two principal components revealed a loading pattern in the frontal plane similar to that found during the voluntary task (figure 3.5B). The first component was predominately pelvis rotation in agreement with the platform rotation while the second component was comprised of trunk and head rotation in the same direction. Timing of the principal components varied between the three angular planes. In the frontal plane, component one began near the start of correction phase I and component two began around the onset of correction phase II (figure 3.5C). However, angular response was delayed in the sagittal and horizontal planes. Perhaps the most striking difference between the leg lift task and surface tilts can be seen in the horizontal plane. During surface tilts, the first eigenvector shows that the head trunk and pelvis all rotated towards the unloaded limb (raised-edge). The second component involved reversal of the pelvis (figure 3.5B).

3.4.3 Knee and Elbow Flexion

Knee and elbow flexion accompanied leg lifting in all directions. Figure 3.6A shows the time course of knee and elbow flexion for one subject. Typically knee flexion of the loaded limb began prior to voluntary movement onset and reached a peak flexion angle between 10° and 15° by 200 ms. On the unloaded side, the start of knee flexion corresponded more closely to movement onset with the exception of back leg lifts which exhibited a preliminary flexion and extension of the limb. Movement in the forward directions (45°, 90°,135°) displayed a large total knee flexion (see figure 3.6B), however by the end of the movement phase, the knee flexion angle returned to near neutral. During posterior leg lifts knee flexion peaked later, but did not return to an extended position although subjects were instructed to maintain a straight leg. As shown in figure 3.6B, knee flexion during platform rotations was almost exclusively associated with the unloaded limb during lateral and diagonal tilts.

Elbow flexion during the movement phase occurred in all directions and on both sides. Note that on the loaded side, the elbow remained flexed whereas on the unloaded side it straightened or hyper-extended. Elbow flexion began approximately 125 ms after platform triggering with no definable pattern.

3.4.4 EMG characteristics

Figure 3.7A illustrates the EMG activation patterns for eight right-sided muscles from a single subject during front diagonal leg lifting (same trial as figures 3.4A and C). Anticipatory muscle activation latencies were recorded and a sample is shown in figure 3.7B. As expected, all muscles activated prior to movement onset. The TA was the only muscle to show any statistical differences due to leg lift direction ($F(9,54)=3.22$, $p<0.05$). Further analysis confirmed that the difference in latency (~50 ms) was a result of stance versus swing limb. For all perturbation directions, the anticipatory phase was exemplified by an early activation of the shank muscles (MG and TA). The TA was recruited on the loaded leg at 242 ms before movement onset while the MG on the unloaded leg was recruited at about the same time (-248 ms). This early activation corresponded to the first lateral shift of the COP. In the unloaded leg, MG activation was followed 50-60 ms later by the AD and TA. RF recruitment began after another 30 ms followed by the ST and TFL at 125 ms before movement onset. When the leg was to be loaded, 100 ms after anticipatory TA recruitment, the AD and RF were activated. MG, ST and TFL were not consistently recruited. Fewer than half of the subjects, often only two, had an anticipatory activation of the trunk muscles. Of those that did, ES latencies were close to movement onset in the back leg lift directions (-30 ms) while the RA was activated considerably earlier (-183 ms).

The amplitude of the EMG response was evaluated by calculating the integrated area during the specified time epochs (see Methods). Data were normalized to the maximal activation for each muscle independent of perturbation direction or task for each subject. Polar plot representations of the average integrated EMG from all nine subjects for the leg lifting task are shown in figure 3.7C. The spatial patterns for the shank and thigh muscles were reasonably consistent across subjects as illustrated by the direction of maximum activation for each subject in figure 3.7C. For the shank, during the anticipatory period, the TA was maximally active on the stance leg during back leg lifts (225°and 270°). In contrast, the MG was maximally active when the leg was lifted to the side or diagonal front (0° and 45°). Typically subjects "kicked" rather than "lifted" their leg in the forward lift directions (45°, 90° and 135°) as was confirmed by an anticipatory plantar flexion of the foot and flexion of the swing limb knee. During both the movement and maintenance phases, the lift direction of maximum activation for the MG switched from the unloaded to the loaded limb. For the thigh muscles, the magnitude of EMG activity was relatively small during the anticipatory phase. The RF was maximally active before lifts to the back (225° and 270°) while the ST was maximally active before forward lifts (90°). During the movement and maintenance phases, the RF was used to lift and hold the swing leg to the front (90R°) as well as control balance at the stance limb during side and back leg lifts (180°, 225° and 270L°). The lift direction of maximum activation for the ST during the movement and maintenance phases was straight back on the unloaded limb for all subjects. The ST was also activated, probably for balance control, during forward lifts (90° and 135°). Hip and trunk muscle activity spatial patterns were more variable across subjects. The RA showed directional specificity only during the anticipatory phase in which the maximal EMG amplitude was found on the loaded side prior to back leg lifts (225° and 270L°). During the anticipatory phase, no ES activation pattern was discernable. However, as expected, leg lifting to the back led to maximum EMG amplitudes during movement and position maintenance phases on the unloaded side (270R° and 315°).

The EMG activation patterns elicited by a diagonal toes-up surface tilt for eight right-sided muscles from a single subject are shown in figure 3.8A (same trial as figures 3.5A and C). Latencies of only three muscles demonstrated sensitivity to perturbation direction (figure 3.8B): TA – $F(7,49)=3.91$, $p<0.002$; MG – $F(7,42)=3.12$, $p<0.05$; RF – $F(7,49)=4.27, p<0.001$. Post hoc analysis indicated that TA recruitment occurred earlier on the unloaded limb following toes-up diagonal tilts (45°) than during a pure toes-up tilt (90°). Since the subject's feet were placed in a 45° outwardly rotated position, this is consistent with the TA's anatomical pulling direction. Both the MG and RF were found to have significantly different latencies for toes-up and diagonal toes-up tilts (45°, 90° and 135°) versus toes-down and diagonal toes-down tilts (225°, 270° and 315°). However, muscle recruitment generally followed a distal-to-proximal strategy. The TA was activated first between 99 and 120 ms after platform onset. In the 0°, 45°, 90°, and 135° directions (i.e. toes-up) TA recruitment was accompanied by coactivation of the MG. Approximately 20 ms later both the RF and AD were activated and followed 20-40 ms later by ST, TFL, RA and ES. Toes-down rotations (180°, 225°, 270° and 315°) began with early recruitment of the TA at 105 ms followed by coactivation of the RF, AD, RA and TFL 20 ms later on average. The first MG, ST and ES bursts occurred approximately 175 ms after platform onset.

Figure 3.8C shows the polar plot representations of the average integrated EMG from multi-directional surface tilts for all nine subjects. Again, the data have been normalized to the maximal activation for each muscle regardless of perturbation direction or task. During correction phase I (70 to 195 ms), the shank muscles displayed sensitivity to perturbation direction. That is, the TA demonstrated larger activation amplitudes following toes-up/unloading tilts (0°, 45° and 90°). As for the MG, the maximum amplitude for half of the subjects was in accordance with the TA while the maximum activation directions for the other four subjects were in response to toes-down/loading tilts (180°, 225° and 270°). As time advanced, the direction of maximum activity for the TA became more focused in the pure toes-up direction. After the initial correction phase, the MG behaved in tandem with the TA in that the direction of maximal output was directly opposite (i.e. 180°, 225° and 270°). The thigh muscles, RF and ST, as well as, the TFL and ES were less well tuned. However, during both the secondary correction phase and the stabilizing phase, the thigh muscles acted in a fashion similar to that of the shank muscles. RF amplitude was greater following loaded diagonal toes-up and lateral perturbations (135° and 180) as opposed to unloaded diagonal toes-down and lateral perturbations (0° and 315°) for the ST. The TFL response was variable across subjects while the AD output was greatest following lateral unloading (0°) for both correction phase I and correction phase II. The trunk muscle, RA, demonstrated directional specificity with regards to activation amplitude only during correction phase I. As expected, it was maximally active following toes-down rotations.

3.5 Discussion

Our results show that when standing subjects are exposed to postural perturbation characterized by a sudden unloading of one foot, the choice of postural strategy is dependent upon perturbation direction particularly during voluntary leg lifting. The primary postural goal for both tasks concerns the control of the body's COM position. Our data provide evidence in support of our hypothesis that the central goal of the nervous system focuses on trunk stabilization and the appropriate use of the center of pressure under the feet to control the whole body COM position during both voluntary and unexpected disturbances to restore postural orientation and equilibrium.

3.5.1 Control of postural orientation through head and trunk stabilization

Our data support the idea that the CNS actively controls displacement of the head and trunk during leg lifting or in response to unexpected surface tilting. The functionality of the displacement is dependent upon both perturbation direction as well as source. Unexpected surface tilting elicits an automatic response strategy which focuses on control of the orientation of the head and trunk with respect to the vertical gravity vector. On the other hand, during fast leg lifting, trunk verticality is compromised for movement generation and the recovery of postural equilibrium while the head is stabilized in space.

Consider, in general, during multi-directional surface tilting the head and trunk behaved as a single "locked" unit. Only at the end of the second balance correction phase did the head uncouple from the trunk and begin to return to its original orientation. Evidence of this linkage is clearly demonstrated by the close relationship between the head and trunk as described by the first and second principal components (figure 3.5B). The actual displacements were relatively small (< 5° on average) and non-existent in some cases. However, these findings are consistent with the concept of a reduction in system redundancy. With the head locked to the trunk, the overall number of joints which the CNS must regulate is reduced. Also, it has been suggested that through joint head-trunk displacement, vestibular receptors can be used to estimate trunk motion and regulate its stability with respect to vertical (Mergner et al. 1993). Our results were not affected by perturbation direction in either the frontal or horizontal planes. However, displacement in the sagittal plane calls for a different strategy. All surface tilts involving a pitch down component produce a backwards displacement of the trunk followed by displacement of the head some 30-50 ms later. This may be an effort by the CNS to stabilize the head position with respect to the earth's horizon thus providing a reference frame for postural stability. These results are in keeping with past research which has demonstrated that when stance is compromised by an unstable surface such that somatosensory information from the feet is less reliable, subjects stabilize their head and trunk more than when the surface is stable (Nashner et al. 1988; Pozzo et al. 1992). Also interesting to note was the frontal plane rotation of the pelvis and head-trunk complex in opposing directions. We believe that this constitutes a control strategy whereby the CNS minimizes COM displacement through head-trunk orientation.

We found further evidence of CNS stabilization of the head in space during voluntary leg lifting. In all leg lift directions, head movement was minimized (~5°) whereas the trunk was displaced between 5° and 15° away from the lifting limb. Our findings are similar to those previously reported by Mouchnino et al. (1992). They found that during lateral leg lifting both naïve subjects and trained dancers maintained a vertical head position. The naïve subjects also inclined their trunks away from the moving leg while the dancers maintained a vertical trunk position. It was proposed that the trunk displacement was required for movement generation as well as postural stability. By inclining the trunk away from the moving limb, COM displacement is minimized in the same way as a board can be balanced on a fulcrum. Similar to the task of voluntary lateral leg lifting (Mouchnino et al. 1992), our subjects began displacing the trunk on or after the focal movement for lifts in the front, front diagonal and lateral directions. However, during back and back diagonal lifts, the onset of trunk displacement preceded the leg lift and subsequent pelvis rotation by as much as 75 ms. We suggest that because of the biomechanical constraints inherent in the directionality of the ankle and knee joints, the anticipatory trunk movement is a strategy used by the CNS to generate thrust force for the upcoming back lift.

Another strategy that our subjects employed to facilitate head and trunk stabilization was knee and elbow flexion (although they were instructed not to do so). We believe that flexion of the unloaded limb following both surface tilts and leg lifts was an effort by subjects to retain vertical trunk orientation and thereby reduce COM displacement. Previous research has shown knee flexion to be a power generation strategy whereby the torque arm created by the leg is shortened and the knee extensors are stretched (Crenna et al. 1987). Flexion of the loaded knee joint lowered the body COM and activated both the thigh and hip muscles. Thus, rotation about the pelvis as opposed to the trunk was facilitated. Elbow flexion, although relatively small in magnitude (~4-6°) accompanied both types of perturbation. If vertical trunk orientation and/or COM displacement are important control variables, even this subtle flexion could be used to reduce trunk acceleration and thus positively impact displacement of the COM towards the support side.

3.5.2 Control of postural equilibrium through COP adjustment

The dynamics of postural equilibrium are related to perturbation source and direction, at least with respect to leg lifting and surface tilting. Regardless of the source of stabilizing forces (e.g. changes in segment orientation, environment or support surface) the outcome is an acceleration of the body's COM that must be controlled for balance to be maintained. One means by which the CNS can counter COM displacement is through adjustments made at the feet-floor interface. Through stimulation of the plantar surfaces of the feet, Roll et al. (2002) and Kavounoudias et al. (1998; 2001) have been able to show that the perception of body posture and orientation are highly dependent upon cutaneous afferents in the feet. Depending upon the stimulation pattern, subjects reported various degrees of "illusionary" whole body leaning. In addition, mechanoreceptors in the feet are known to provide important information concerning both perturbation velocity (Diener et al. 1988) and direction (Macpherson 1994) as illustrated by EMG activity. The significance of somatosensory feedback has been shown in altered environments such as microgravity (Massion et al. 1997). Also, it has been suggested that, at least in conjunction with self-initiated movement, end position balance rather than body orientation has been preprogrammed by the CNS (Do et al. 1991). Subjects were asked to perform a ballistic flexion-extension of the lower leg and end either standing on one or two legs. Significant differences with respect to kinematic and EMG variables were found between the two tasks, leading to the conclusion that final position equilibrium was centrally programmed. Couillandre et al. (2000) and Nolan and Kerrigan (2003) have reported similar adaptations to the anticipatory phase of gait initiation when subjects were asked to perform toe-walking versus normal heel-to-toe-walking. The initial foot posture partially prevented the characteristic backward shift of the COP, which is typically employed for the generation of forward momentum in gait. To achieve the necessary gait velocity for forward progression during toe-walking, the duration of the anticipatory COP shift was increased.

If postural equilibrium takes priority over orientation, then the interface of the feet with the support surface becomes a significant source of balance control. Our analysis of the temporal relationship between COM and COP during voluntary leg lifts demonstrated the use of advanced changes in COP position to control COM displacement. Also, once the target position was reached (i.e. position maintenance phase), the COM was encompassed by an oscillating COP. Other researchers have reported similar findings in relation to voluntary movement. Clear evidence of the central control of COM positioning through COP shifts has been shown in tasks involving adaptation of the support configuration (Kaminski and Simpkins 2001; Lyon and Day 1997; Mille and Mouchnino 1998). Lifting one foot will decrease the base of support substantially and induce a fall if the COM is not repositioned over the stance foot. An increase in the ground reaction forces under the swing leg, which serves to propel the COM towards the stance limb, has been found to precede leg lifting and is scaled in order to reestablish posture and equilibrium (Lyon and Day 1997; Mille and Mouchnino 1998). This anticipatory response is not seen in supine leg lifting (McIlroy et al. 1999) or during leg lifting in microgravity (Mouchnino et al. 1996), when there is no interface between the feet and the environment. We also found a similar relationship between COM and COP following unexpected surface tilts.

With respect to quiet stance, Winter and colleagues have developed a theory for the control of posture through changes in the COP (1998; 1996). By analyzing COP movement in both A/P and M/L directions with respect to loading and unloading, they have been able to describe a "complex" CNS control strategy based on percentages of more simple single (ankle) and double (hip) inverted pendulum models. This theory is particularly interesting since it reduces the number of postural responses and appears to be sensitive to biomechanical constraints as well as perturbation direction. For instance, they have shown that the strategy behind COP shifts is dependent upon stance configuration. With feet in parallel, one next to the other, A/P balance was controlled through plantar/dorsiflexion while M/L control was the result of hip abduction/adduction. In tandem stance, the controls were reversed. However, when subjects were required to stand in a position mimicking the double limb support phase in gait, both ankle and hip mechanisms were found to contribute to M/L movement while A/P control required the ankle to cancel out the effects of the hip. In our experiments, the initial stance position involved 45° of toe-out. Thus, overall COP displacement was reduced in the A/P direction, but our data can still be shown to reflect a combined ankle-hip strategy as demonstrated in part by the sensitivity to perturbation direction.

Stapley and Pozzo (1998) argued that COM "stabilization" might not be a primary control variable, at least with respect to whole body reaching. They proposed a model which involved the controlled displacement of the COM within the base of support. Thus, to maintain posture and balance, some internal knowledge of movement boundaries, environmental conditions, and segmental orientation as well as COM positioning is required. Gurfinkel et al. (1995) have described this control in terms a dual-regulatory system. The lowest level of control is concerned with COM positioning and relies on visual, vestibular in addition to proprioceptive feedback. The second, higher control level is used by the CNS to fine tune movement performance and involves transformation of external information to an internal reference system. Alignment of the gravity vector and the longitudinal body axis were used to achieve stable posture. Furthermore, it has been suggested that sensory receptors near the actual COM position may be actively involved in the control of posture (Mittelstaedt 1998). In our case, COP displacement did not always precede COM movement and early displacement of the trunk and pelvis were accompanied by knee and elbow flexion during voluntary and involuntary changes in the base of support. Therefore, we believe that COM control is a dynamic rather than static task.

3.5.3 Voluntary versus automatic adjustment

Through the comparisons of voluntary versus unexpected postural responses, we can explore how the CNS integrates feedforward and feedback information. A system whose control mechanisms are adaptable as well as context dependent would have a greater flexibility to compensate for a variety of instabilities whether they arose from self-generated or externally imposed movements.

We found many similarities in the postural response strategies following voluntary leg lifting versus unexpected surface tilting. Perhaps the most significant refers to the reduction of joint segment redundancy as illustrated by the head, trunk and pelvis coordination. It may be possible on a very simplistic level, to equate the different strategies that we observed with variations of the "ankle" and "hip" strategies as previously described for stance (Horak and Nashner 1986; Winter et al. 1998; Winter et al. 1996). Or, perhaps, more appropriately, as a continuum of strategies as Kuo and Zajac have proposed in their model of feasible COM accelerations (1993). Consider, during lateral and diagonal surface tilts as well as front and front diagonal leg lifts, pelvis rotation, in opposition to head or trunk movement, dominated the response. However, during pure pitch plane surface tilts and back, back diagonal and side leg lifts the trunk and pelvis moved in harmony as if the body was an inverted pendulum. The externally rotated foot position that our protocol required benefited M/L stabilization by increasing the width of the base of support, even though hip control was still apparent. We found the AD muscle maximally activated during limb unloading and the TFL tuned with limb loading. This is not unlike the pairing of the AD in the unloaded limb with the TFL in the loaded limb during voluntary leg flexion (Rogers and Pai 1995). However, during multidirectional leg lifting, we found co-contraction of the AD and TFL in all lift directions. This discrepancy may be due to different task goals and biomechanical constraints (i.e. stiffening the pelvis to accommodate the long lever arm and to control medial-lateral stability). In addition, most of our subjects relied on flexion of the support limb knee to lower their COM and enable better use of the thigh and hip muscles. Also, the use of the arms as a balance tool undoubtedly reduced the magnitude of the postural responses. The ability to successfully shift weight from side-to-side has been shown to be noticeably absent in stroke subjects (Kirker et al. 2000). A sideways push to the hemiparetic side of stroke patients during standing resulted in small and late activation of the gluteus medius on the paretic side as compared to control subjects, while a push to the unaffected side elicited no contralateral adductor activation. Activation patterns of the hemiparetic muscles were also impaired during gait initiation, while activation during cyclical stepping more closely resembled the controls. These results led to the conclusion that medial-lateral stabilization is centrally controlled and thus, lacking following stroke.

In conclusion, our study of postural response strategies during multi-directional leg lifts and unexpected surface tilts found that balance corrections were sensitive to the perturbation direction. Furthermore we have provided evidence of redundancy reduction through the CNS recruitment of specific postural strategies to oppose postural instability. We suggest that, at least during voluntary leg lifts and unexpected surface tilts, the CNS dynamically controls COM displacement through adjustments to head and trunk orientation and COP positioning.

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3.7 Tables & Figures

Table 3.1 Percent variance explained by the eigenvalues of the head-trunk-pelvis angle covariance matrix during voluntary leg lifts

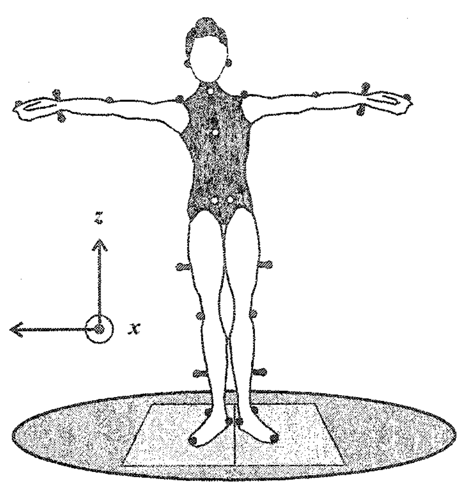
		Sagittal	Frontal	Horizontal
0°	λ_1	89 ± 10.3	99 ± 1.7	91 ± 9.2
	λ_2	9 ± 8.9	1 ± 1.6	7 ± 8.0
	λ_3	2 ± 2.0	0 ± 0.2	1 ± 1.7
45°	λ_1	94 ± 7.1	97 ± 3.5	88 ± 9.7
	λ_2	5 ± 6.3	3 ± 3.4	10 ± 8.6
	λ_3	1 ± 1.5	0 ± 0.3	2 ± 1.7
90°	λ_1	97 ± 3.7	93 ± 9.1	93 ± 9.8
	λ_2	3 ± 3.4	7 ± 8.5	6 ± 8.8
	λ_3	1 ± 0.5	1 ± 1.1	1 ± 1.5
135°	λ_1	94 ± 7.1	96 ± 4.5	87 ± 11.3
	λ_2	5 ± 6.8	4 ± 4.2	12 ± 10.0
	λ_3	1 ± 0.7	0 ± 0.5	2 ± 1.8
180°	λ_1	91 ± 8.9	98 ± 1.7	86 ± 10.7
	λ_2	7 ± 7.9	1 ± 1.6	12 ± 9.5
	λ_3	2 ± 1.9	0 ± 0.2	2 ± 2.1
225°	λ_1	98 ± 2.7	99 ± 1.3	87 ± 11.2
	λ_2	2 ± 2.2	1 ± 1.2	11 ± 9.9
	λ_3	0 ± 0.7	0 ± 0.2	2 ± 1.6
270°	λ_1	98 ± 2.3	96 ± 5.9	87 ± 10.8
	λ_2	2 ± 2.1	3 ± 5.1	12 ± 9.3
	λ_3	0 ± 0.3	1 ± 1.2	2 ± 2.6
315°	λ_1	98 ± 4.0	98 ± 2.7	88 ± 10.8
	λ_2	2 ± 3.9	2 ± 2.7	11 ± 9.6
	λ_3	0 ± 0.5	0 ± 0.2	2 ± 2.1

Table 3.2 Percent variance explained by the eigenvalues of the head-trunk-pelvis angle covariance matrix from unexpected surface tilts

		Sagittal	Frontal	Horizontal
0°	λ_1	88 ± 7.8	96 ± 3.9	91 ± 7.8
	λ_2	10 ± 5.4	4 3.8	8 ± 6.7
	λ_3	3 ± 3.1	0 ± 0.3	1 1.9
45°	λ_1	86 ± 10.2	94 ± 8.3	91 ± 9.0
	λ_2	12 ± 9.2	6 ± 7.6	8 ± 8.3
	λ_3	2 ± 1.8	1 ± 0.9	1 ± 1.2
90°	λ_1	85 ± 7.1	82 13.9	90 ± 9.7
	λ_2	12 ± 5.6	15 ± 12.8	8 7.0
	λ_3	3 ± 2.2	2 ± 2.7	2 ± 3.1
135°	λ_1	86 ± 9.7	96 ± 5.8	92 ± 8.7
	λ_2	12 ± 8.8	4 ± 5.6	7 ± 7.8
	λ_3	2 ± 2.1	0 ± 0.5	1 ± 1.5
180°	λ_1	84 ± 12.1	97 ± 5.3	92 ± 8.4
	λ_2	13 ± 10.4	3 ± 5.2	7 ± 7.4
	λ_3	3 ± 2.9	0 ± 0.2	1 ± 1.4
225°	λ_1	85 ± 11.4	96 ± 6.7	92 ± 11.2
	λ_2	13 ± 10.3	4 ± 6.0	7 ± 9.2
	λ_3	3 ± 2.1	1 ± 0.9	1 ± 2.7
270°	λ_1	79 ± 13.1	86 ± 11.2	87 ± 10.8
	λ_2	17 ± 10.6	11 ± 9.9	11 ± 9.8
	λ_3	4 ± 4.2	3 ± 2.4	2 ± 2.0
315°	λ_1	82 ± 12.4	95 ± 5.2	92 ± 8.1
	λ_2	14 ± 9.4	4 ± 4.7	7 ± 6.5
	λ_3	4 ± 4.1	0 ± 0.7	1 ± 2.3

Figure 3.1 A) Kinematic set-up with 34 markers. Small circles show reflective marker placement (white circles represent posterior trunk and pelvis markers). The kinematic coordinate system (x y z) is shown on the side. B) Coordinate system for both voluntary leg lifts and unexpected surface tilts. Arrow indicates raised leg or surface edge. Insets show loading and unloading forces from a representative subject (black lines – right force plate; gray lines – left force plate). Solid lines are from the leg lift task and dashed lines correspond to surface tilts.

A. Kinematic set-up



B. Perturbation directions and coordinates

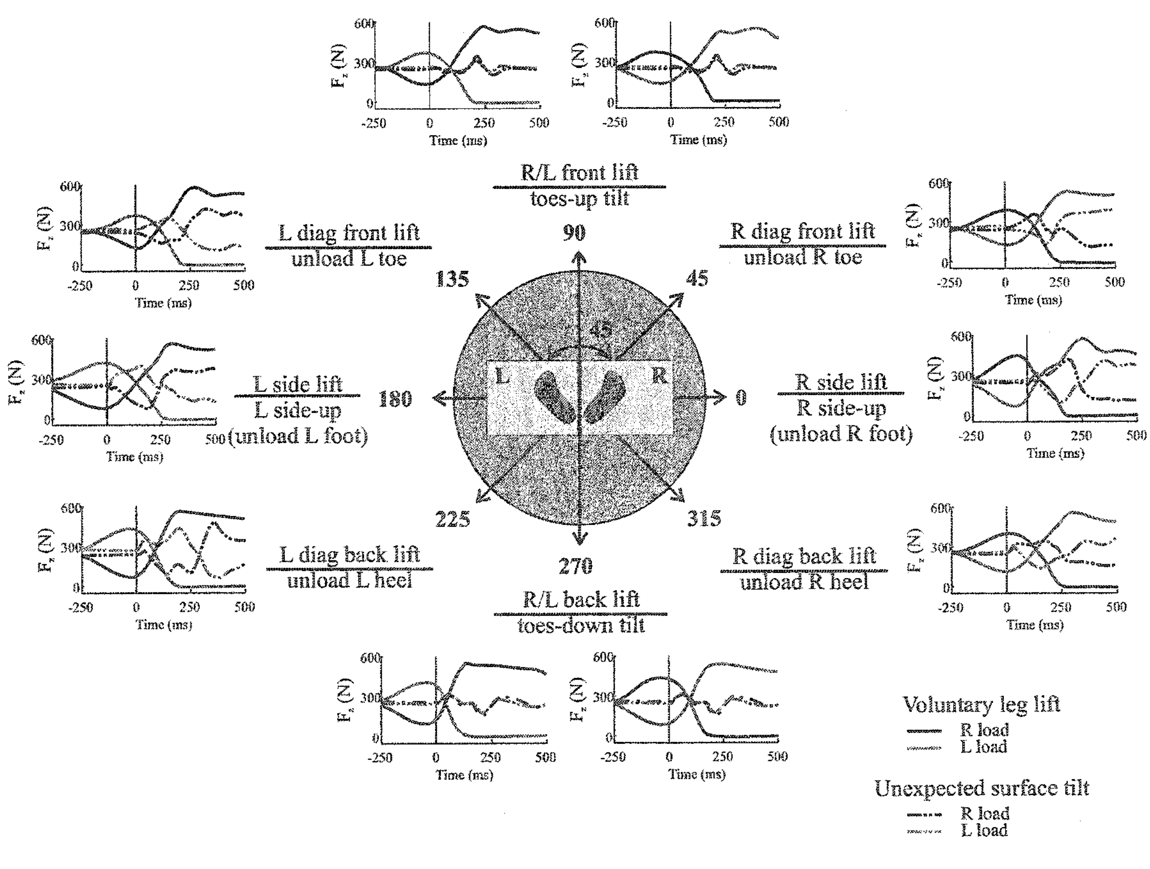
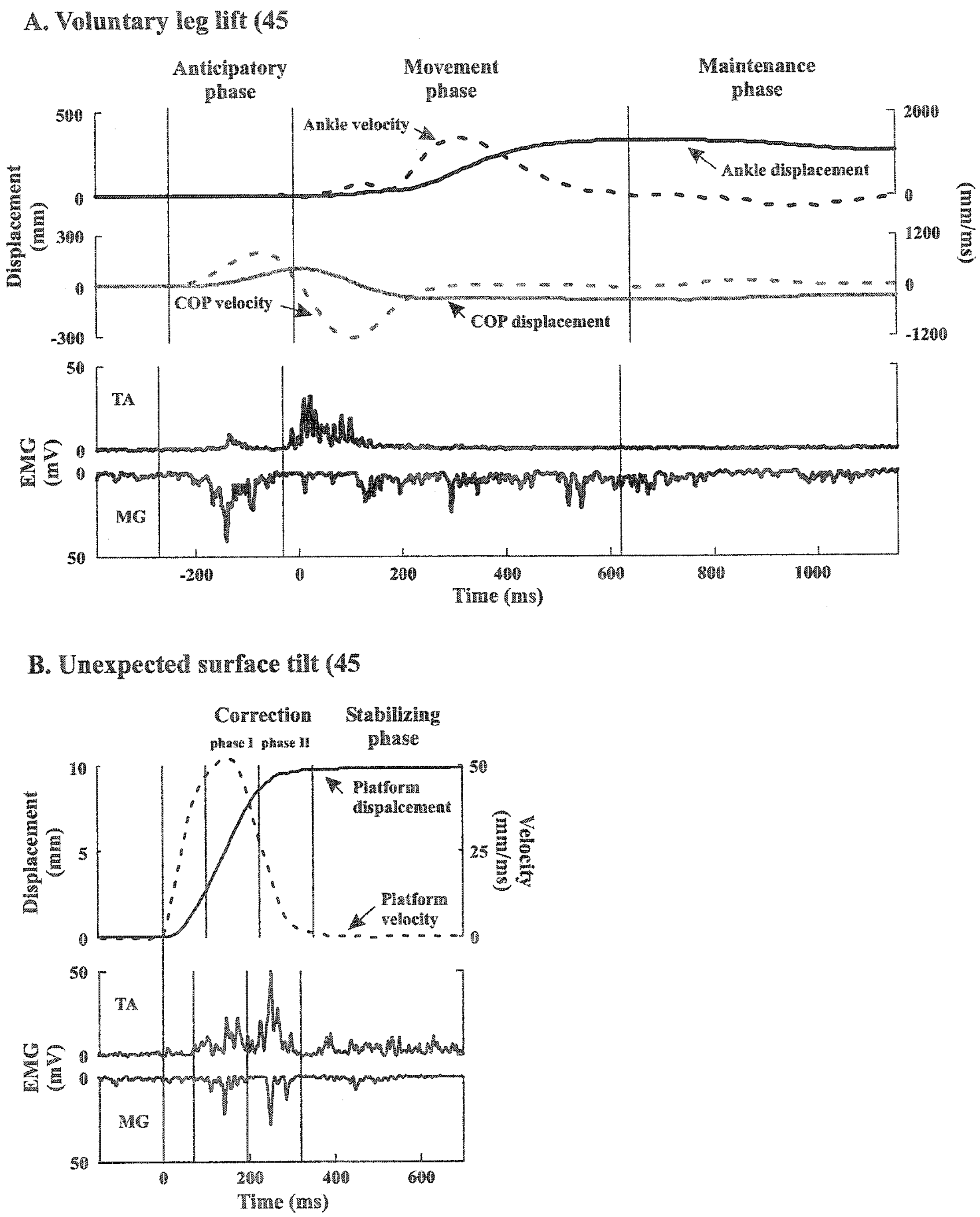


Figure 3.2 Time intervals. A) Voluntary leg lifts. Vertical ankle displacement and velocity (z-direction), COP displacement and velocity (medial-lateral) and shank muscle activation during right diagonal front leg lift (45°) for a representative subject. B) Unexpected surface tilts. Platform rotation/velocity (z-direction) and shank muscle activation during right diagonal toes-up rotation for the same subject. Note: kinematic integrals are offset from EMG by 30 ms.



A. Voluntary leg lift (45
Anticipatory phase
Movement phase
Maintenance phase
Displacement (mm)
Velocity (mm/ms)
500
0
300
0
-300
2000
0
1200
0
-1200
Ankle velocity
Ankle displacement
COP velocity
COP displacement
EMG (mV)
50
0
0
50
TA
MG
-200
0
200
400
600
800
1000
Time (ms)
B. Unexpected surface tilt (45
Correction
phase I phase II
Stabilizing phase
Displacement (mm)
Velocity (mm/ms)
10
5
0
50
25
0
Platform dispalcement
Platform velocity
EMG (mV)
50
0
0
50
TA
MG
0
200
400
600
Time (ms)

Figure 3.3 COM/COP. A) Average COM/COP peak-to-peak displacements over entire trial for all nine subjects. Black triangles refer to COM (+SE); gray triangles refer to COP (+SE). Note scale magnitudes: A/P displacement is one/third the size of M/L displacement. B) Ensemble average horizontal plane trajectories of COM and COP for right side leg lifts and right side-up surface tilts (left side is a mirror image). Displacement begins at zero-zero.

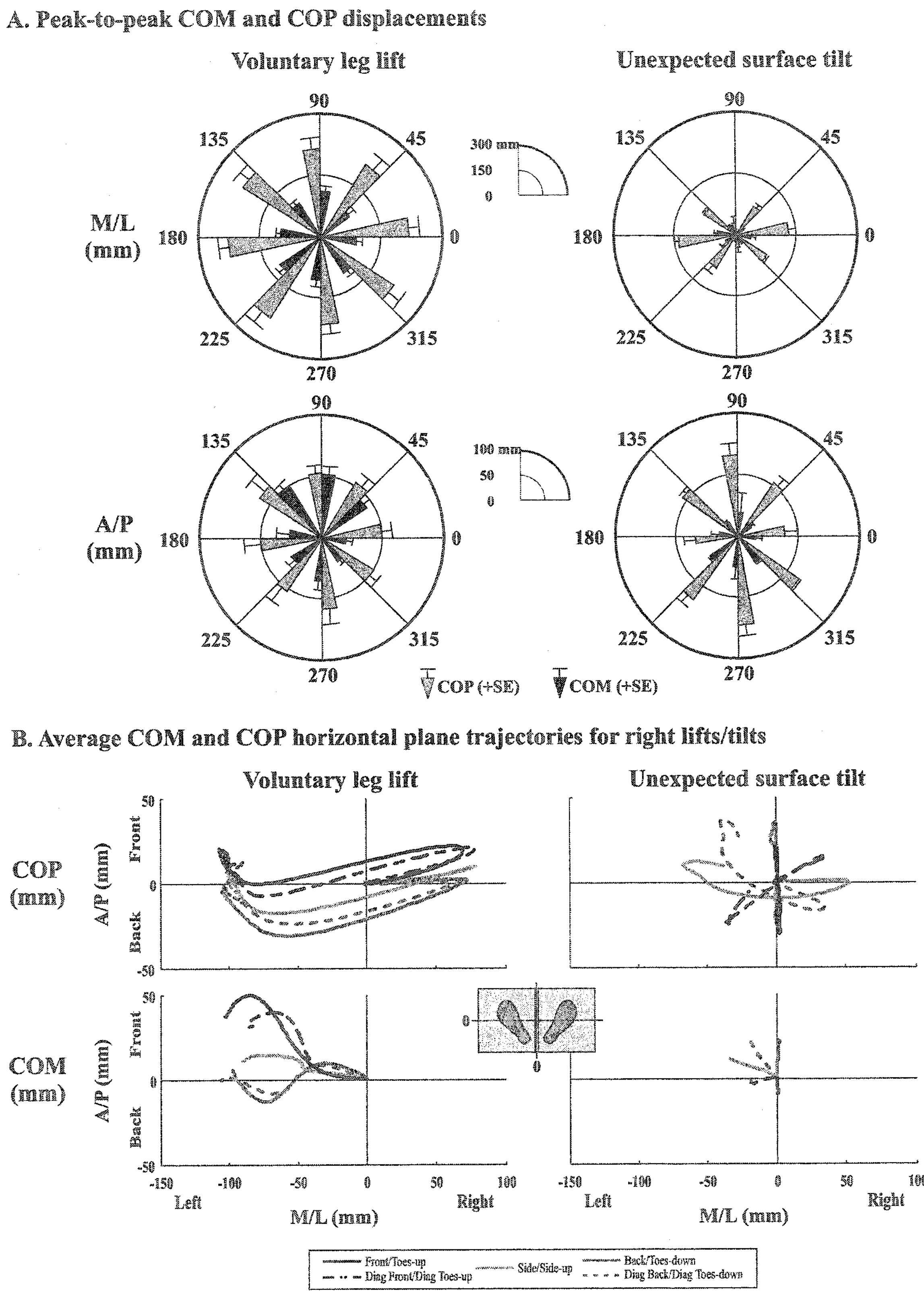
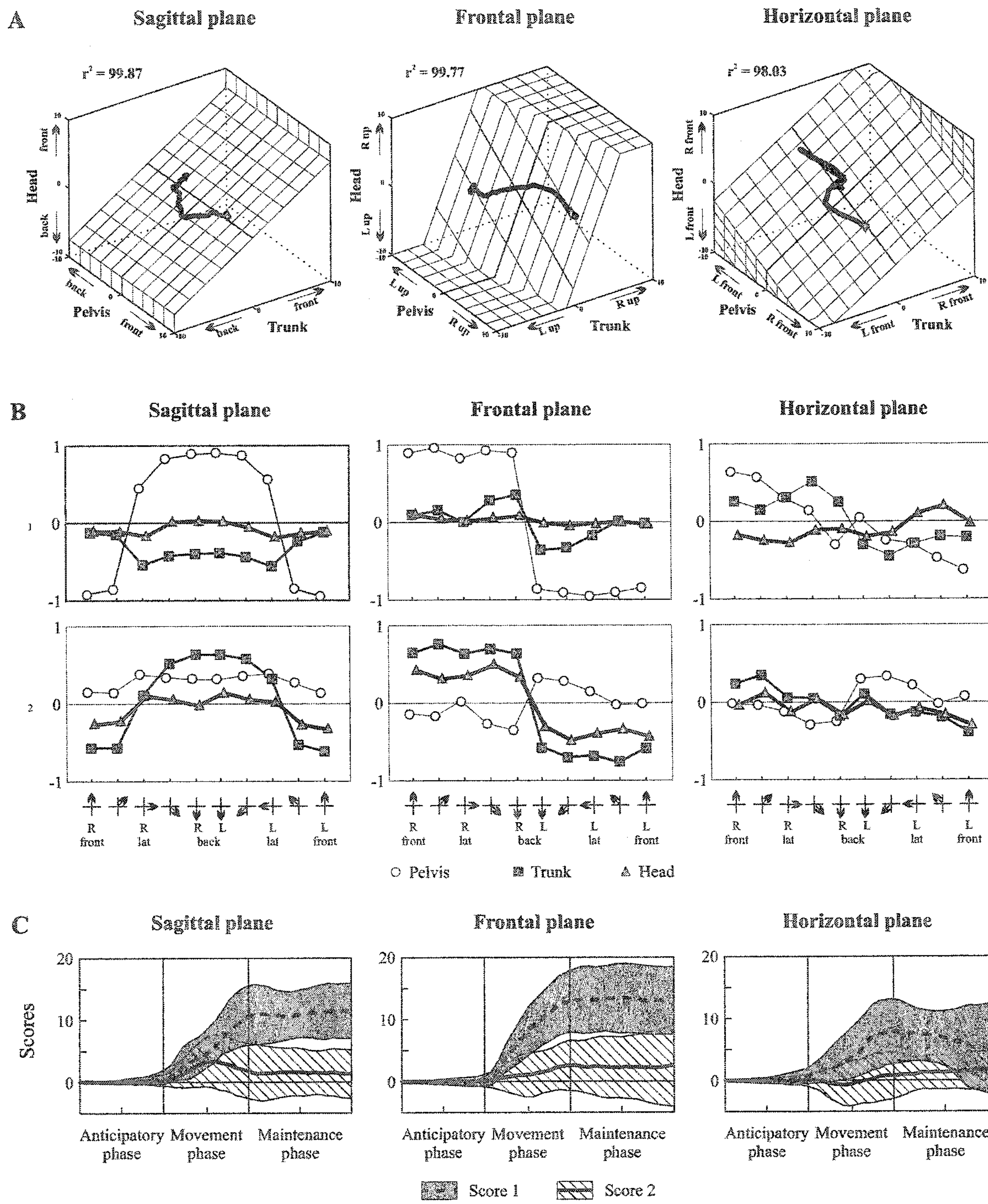
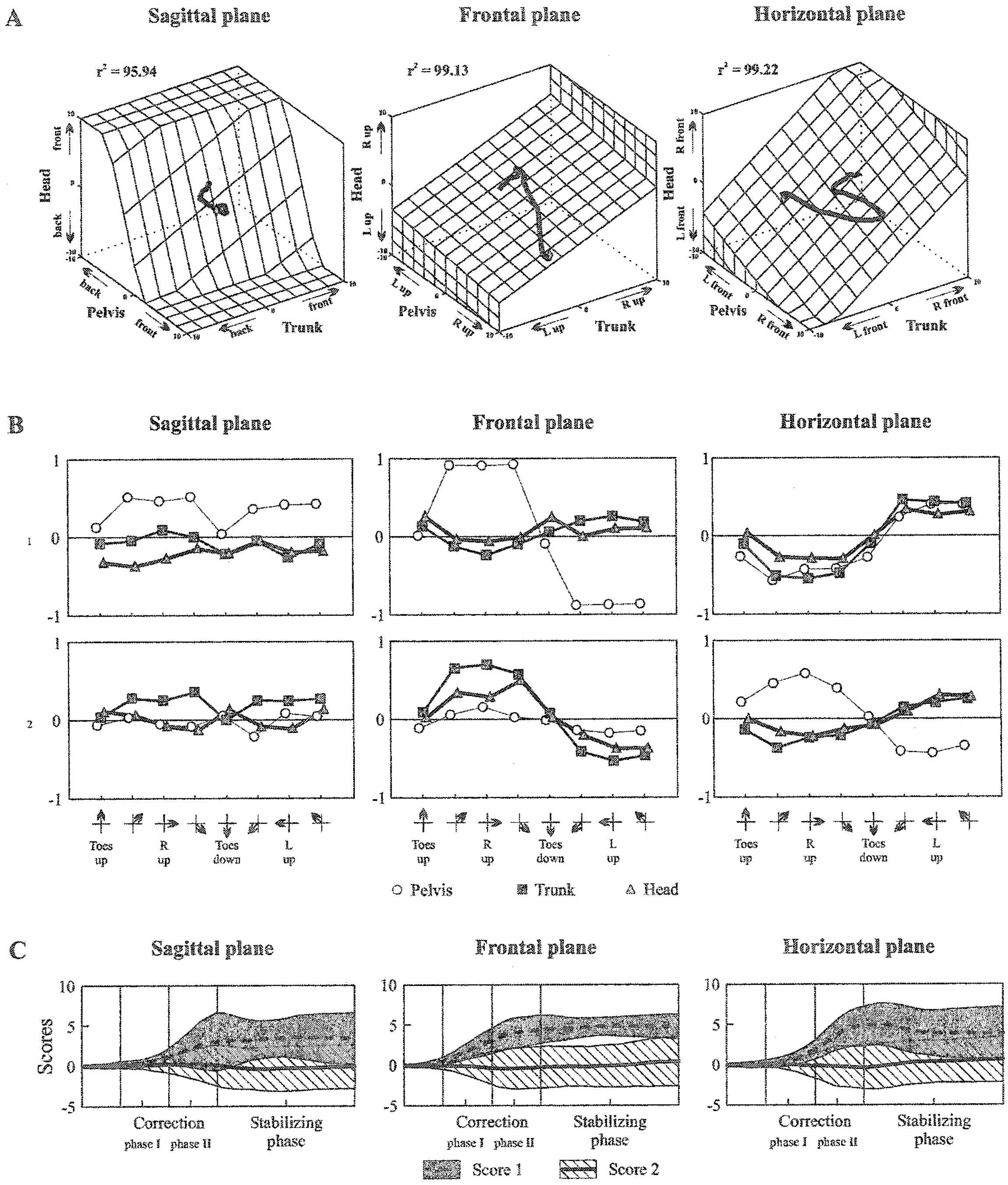

A. Peak-to-peak COM and COP displacements
Voluntary leg lift
Unexpected surface tilt
M/L
(mm)
A/P
(mm)
90
45
0
315
270
225
180
135
300 mm
150
0
100 mm
50
0
COP (+SE)
COM (+SE)
B. Average COM and COP horizontal plane trajectories for right lifts/tilts
Voluntary leg lift
Unexpected surface tilt
COP
(mm)
COM
(mm)
A/P (mm)
Front
Back
50
0
-50
-150
-100
-50
0
50
100
Left
Right
M/L (mm)
Front/Toes-up
Diag Front/Diag Toes-up
Side/Side-up
Back/Toes-down
Diag Back/Diag Toes-down

Figure 3.4 Voluntary leg lifts. A) 3-dimensional plot of head, trunk and pelvis displacement for the sagittal, frontal and horizontal planes. Data are from a left diagonal front leg lift from a single representative subject. The gray diamond indicates beginning of displacement. The data have been fit by a plane described by the first two eigenvectors. > 98% of the variance was described by the planes. B) First and second eigenvector loadings for the sagittal, frontal and horizontal planes. Sign (+/-) is indicative of displacement direction. Black circles represent the pelvis, dark gray rectangles the trunk and light gray triangles the head. Bars indicate standard error. C) Average scores and standard errors for the first and second principal components from all nine subjects in the left diagonal front leg lift direction. The black line surrounded by dark gray represents the first score; the black line surrounded by hatching indicates the second.



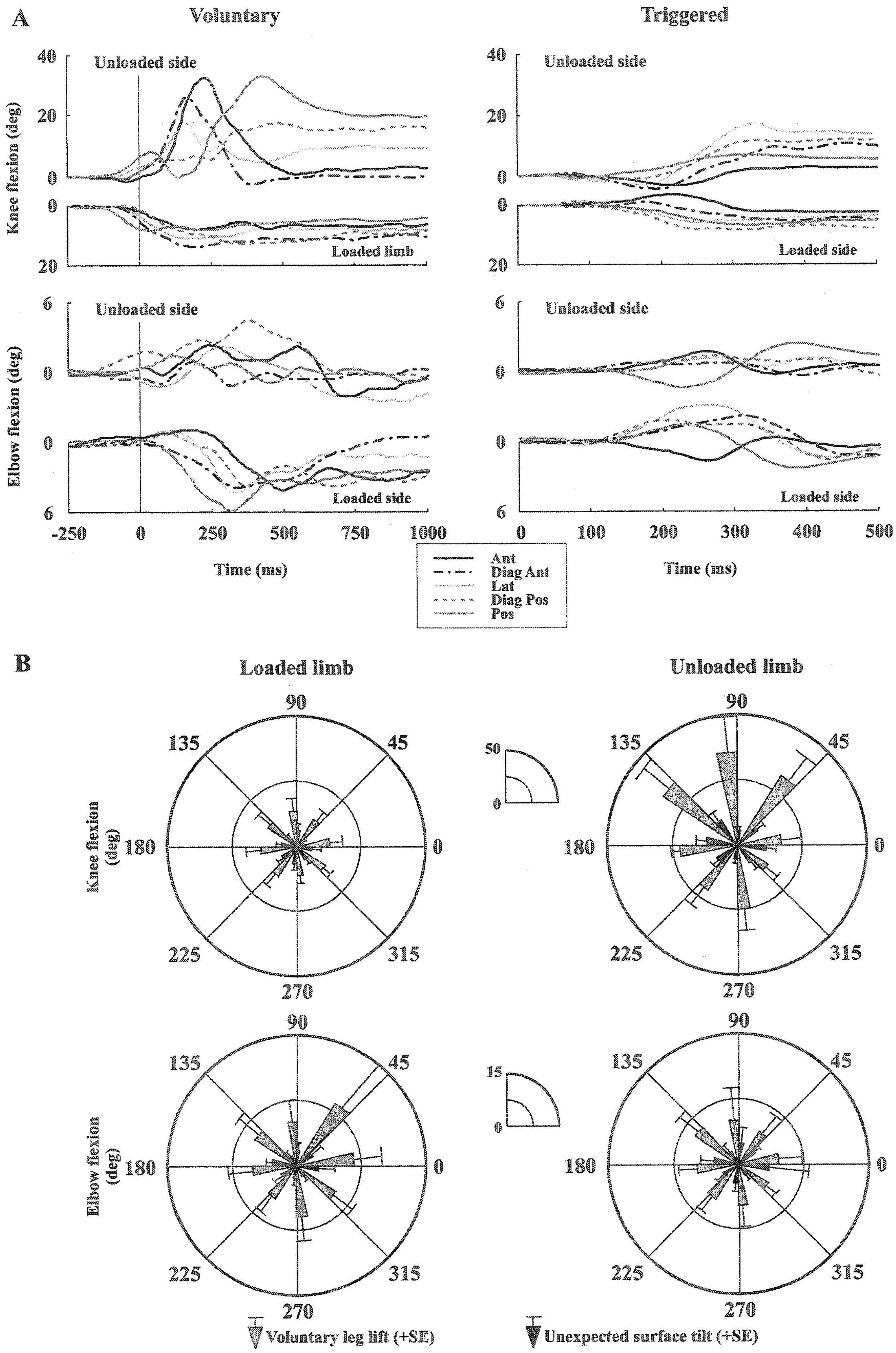
A
Sagittal plane
Frontal plane
Horizontal plane
r² = 99.87
r² = 99.77
r² = 98.03
Head
front
back
R up
L up
R front
L front
Pelvis
Trunk
B
Sagittal plane
Frontal plane
Horizontal plane
R front
R lat
R L back
L lat
L front
○ Pelvis
Trunk
△ Head
C
Sagittal plane
Frontal plane
Horizontal plane
Scores
Anticipatory phase
Movement phase
Maintenance phase
Score 1
Score 2

Figure 3.5 Unexpected surface tilts. A) 3-dimensional plot of the head, trunk and pelvis displacement for the sagittal, frontal and horizontal planes. Data are from a left diagonal toes-up surface tilt from the same subject as figure 4A. Gray diamond indicates beginning of displacement. Conventions as in figure 4A. B) First and second eigenvector loadings for the sagittal, frontal and horizontal planes for all eight perturbation directions. C) Average scores and standard errors for the first and second principal components from all nine subjects in the left diagonal toes-up tilt direction.



A
Sagittal plane
Frontal plane
Horizontal plane
r² = 95.94
r² = 99.13
r² = 99.22
Head
Pelvis
Trunk
front
back
R up
L up
R front
L front
B
Toes up
R up
Toes down
L up
○ Pelvis
Trunk
△ Head
C
Scores
Correction
phase I
phase II
Stabilizing phase
Score 1
Score 2

Figure 3.6 Knee and elbow flexion. A) Knee and elbow flexion during voluntary leg lifts (left column) and unexpected surface tilts (right column) from a single block from a representative subject. B) Average peak-to-peak knee and elbow flexion for the loaded (left column) and unloaded (right column) limbs from nine subjects over the entire trial. Black triangles indicate surface tilt data (+SE); gray triangles indicate leg lift data (+SE).



A
Voluntary
Triggered
Knee flexion (deg)
Unloaded side
Loaded limb
Loaded side
Elbow flexion (deg)
Time (ms)
Ant
Diag Ant
Lat
Diag Pos
Pos
B
Loaded limb
Unloaded limb
Knee flexion (deg)
Elbow flexion (deg)
Voluntary leg lift (+SE)
Unexpected surface tilt (+SE)

Figure 3.7 Muscle activation during voluntary leg lifts. A) Example EMG data from shank (TA-dark, MG-light), thigh (RF-dark, ST-light), hip (TFL-dark, AD-light) and trunk (RA-dark, ES-light) muscles during a diagonal front leg lift from a typical subject. Left column contains loaded limb data and right column contains data from the unloaded limb. B) Anticipatory muscle activation pattern (averaged data is from front diagonal leg lifts). Note early activation of the shank muscles and late TFL activation. C) Muscle tuning curves representing integrated EMG over anticipatory and movement phases. Maintenance phase is similar to the movement phase. Data has been normalized to lift cycles and maximum activation as described in the methods section. Small *** (TA,RF,TFL,RA) and °°° (MG,ST,AD,ES) show direction of maximum activation for each subject. Outside circle represents 30,000 units. Note: left half of curve (light gray) contains unloaded limb data and right half of curve (white) shows data from the loaded limb.

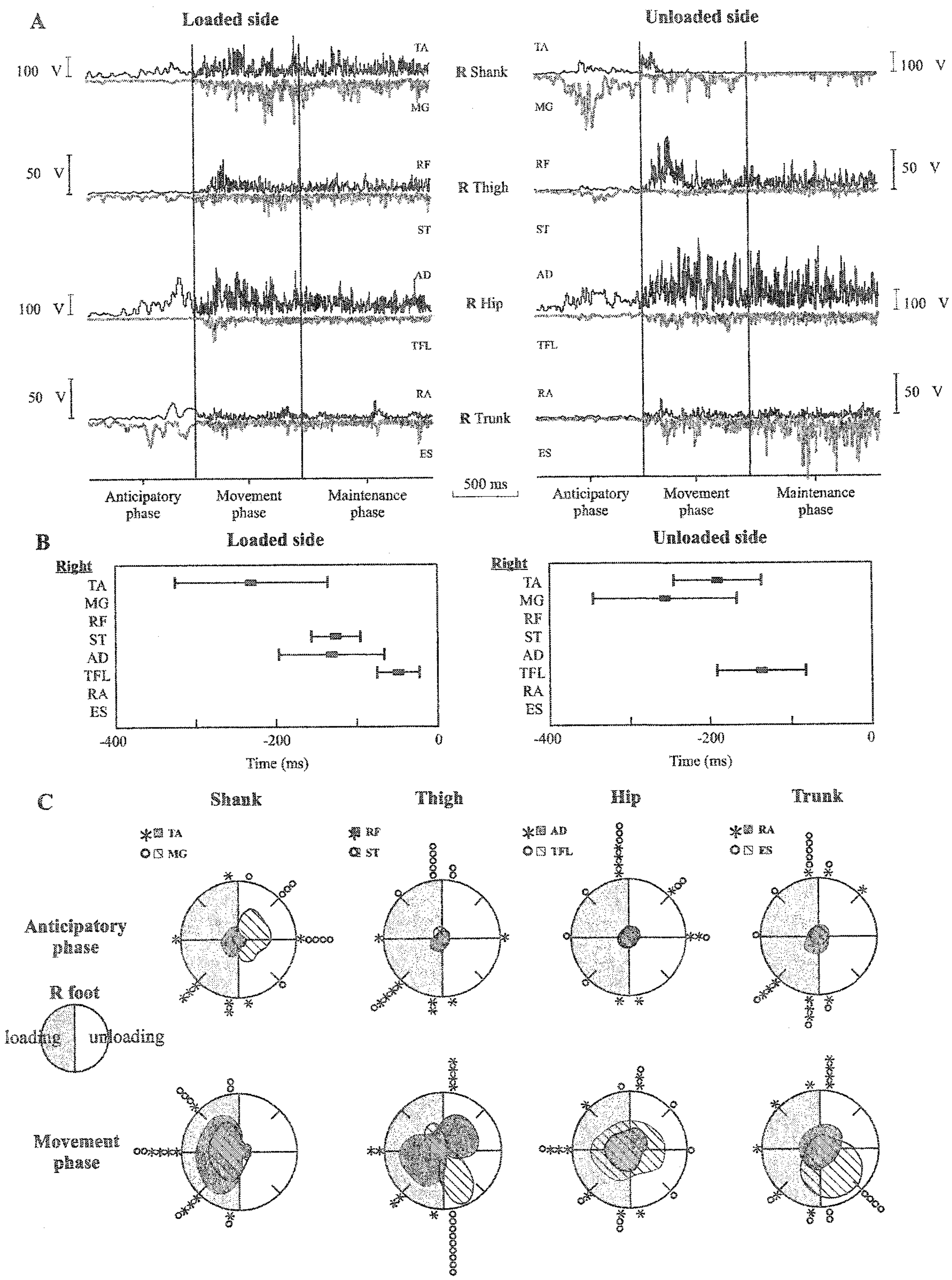
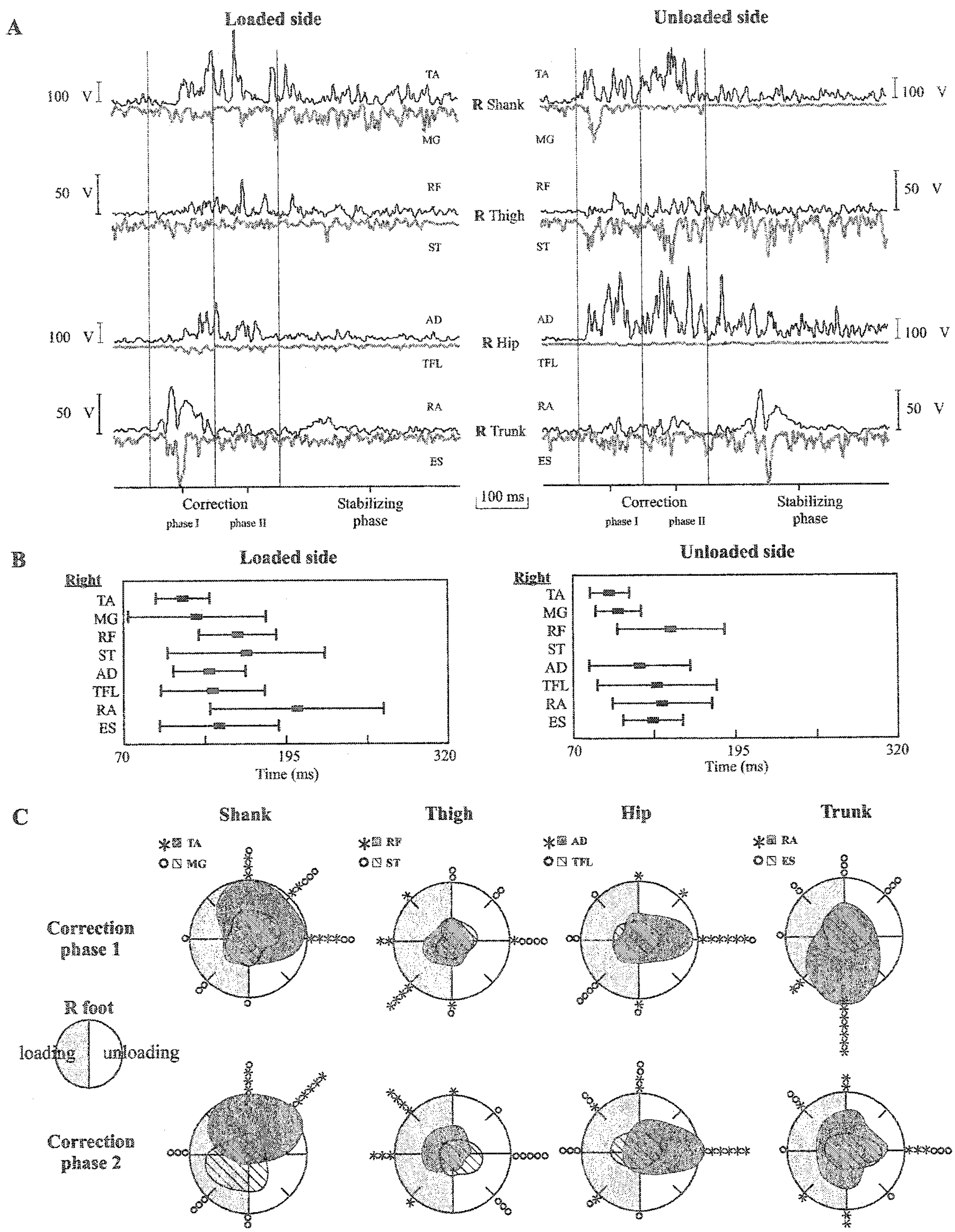

A
Loaded side
Unloaded side
TA
MG
R Shank
RF
ST
R Thigh
AD
TFL
R Hip
RA
ES
R Trunk
100 V
50 V
500 ms
Anticipatory phase
Movement phase
Maintenance phase
B
Loaded side
Unloaded side
Right
TA
MG
RF
ST
AD
TFL
RA
ES
-400
-200
0
Time (ms)
C
Shank
Thigh
Hip
Trunk
TA
MG
RF
ST
AD
TFL
RA
ES
Anticipatory phase
R foot
loading
unloading
Movement phase

Figure 3.8 Muscle activation during unexpected surface tilts. A) Example EMG data from shank, thigh, hip and trunk muscles during a diagonal toes-up surface tilt from the same subject as figure 7A. For conventions refer to figure 7A. B) Reactive muscle activation pattern (averaged data is from diagonal toes-up surface tilts). Note early activation of the shank muscles. C) Muscle tuning curves representing integrated EMG over correction phase I (70-195 ms) and correction phase II (195-320 ms). Stabilizing phase is similar to correction phase II. Small *** (TA,RF,TFL,RA) and °°° (MG,ST,AD,ES) show direction of maximum activation for each subject. Outside circle represents 3,000 units, one-tenth the magnitude during voluntary leg lifts.


A
Loaded side
Unloaded side
TA
MG
R Shank
RF
ST
R Thigh
AD
TFL
R Hip
RA
ES
R Trunk
100 V
50 V
100 ms
Correction
phase I
phase II
Stabilizing phase
B
Loaded side
Unloaded side
Right
TA
MG
RF
ST
AD
TFL
RA
ES
70
195
320
Time (ms)
C
Shank
Thigh
Hip
Trunk
TA
MG
RF
ST
AD
TFL
RA
ES
Correction phase 1
R foot
loading
unloading
Correction phase 2

Chapter 4 The control of balance in skilled ballet dancers and recreational athletes: I. multi-directional leg lifts

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Submitted to: Journal of Neurophysiology August 2003

The normal control of posture and balance during voluntary leg lifting and unexpected surface tilting is investigated in active young people. A detailed description of the postural strategies commonly used by these individuals to perform a fast leg lift is presented in this chapter. High level athletic training in sports which require precision as well as successful movement performance has been shown to modify normal response parameters (Mouchnino et al. 1992; Pedotti et al. 1989). Therefore, in a task for which athletes have been specifically trained, the control of posture by these individuals should reflect the constraints of the particular discipline (Marin et al. 1999). Also, inter-individual variability should be reduced (Mouchnino et al. 1992). Classical ballet dancers provide a unique study group in that balance, segmental orientation as well as the "quality of movement" is practiced on a daily basis. One of the constraints placed on classical dancers by their discipline is the control of upright vertical posture. From an early age, dance students are instructed to keep the trunk stable in space while the limbs move about freely. As was shown in Chapter 3, non-dancers sacrifice vertical trunk alignment in order to perform fast leg lifts. Dancers, on the other hand, should be expected to retain vertical alignment and thereby perform the lifts in a more efficient manner (Mouchnino et al. 1992). By comparing and contrasting the postural control strategies used by classically trained dancers and active non-dancers during voluntary leg lifting, we provide further insight into the plasticity of the central nervous system.

4.1 Abstract

We studied changes in postural control strategy associated with high level ballet training during multi-directional leg lifting. Female ballet dancers and active non-dancers were instructed to lift one leg as fast as possible in one of five directions (front, 45° diag front, side, 45° diag back and back) to a 45° height. Center of mass (COM) and center of pressure (COP) displacements, as well as three-dimensional (3-D) angular changes in head, trunk and pelvis orientation were evaluated. We also examined muscle activation patterns for right-sided trunk and lower limb muscles. Significant differences between groups were found with respect to anterior/posterior COP displacement and three-dimensional COM excursion. No differences in lateral COP or COM displacements were found. Principal component analysis of 3-D angular excursions revealed different control strategies between dancers and non-dancers. For all directions, the first principal component revealed that dancers minimized head and trunk displacement through pelvis rotation while non-dancers displaced the head and trunk. The second component showed that dancers were able to use horizontal pelvis rotation to achieve stabilization, while non-dancers did not possess this level of control. Anticipatory muscle responses were smaller for dancers. Non-dancers activated all muscles tested. In addition, dancers muscle responses were more sensitive to lift direction than non-dancers. These results show that classical dance training leads to a functional adaptation of the postural control strategy associated with fast leg lifting. Dancers are able to maintain a more vertical trunk alignment than active non-dancers who use trunk displacement to facilitate leg lifting

4.2 Introduction

When a standing person performs a voluntary movement, the vertical upright posture is affected by both reactive forces and changes in body geometry. To maintain balance and equilibrium, postural adjustments must be made to ensure that the body's center of mass (COM) remains within the base of support. However, the means by which this goal can be achieved are endless. It has been suggested that through learning and experience, the central nervous system (CNS) is able to implement a postural plan or strategy which will facilitate movement production and act to overcome upcoming instabilities (Horak and Macpherson 1996; Massion 1992).

Recent research suggests that postural strategies are highly adaptive and task dependent. Muscle response latencies, activation amplitudes and recruitment patterns are mutable, depending on the specific perturbation (Le Pellec and Maton 1999). By analyzing the anticipatory postural adjustments which accompany vertical jumping, Le Pellec and Matton (1999) have demonstrated a direct relationship between jump height and shank muscle activation/deactivation latencies. Further, environmental conditions such as weightlessness (Massion et al. 1998) or a decrease in surface friction (Shiratori and Latash 2000) have been shown to affect central response patterns. Even individual biomechanical constraints can lead to strategical variability (Kolb and Fischer 1994). Moreover, postural responses can be influenced by previous experience (Hore et al. 1994; Timmann and Horak 1997), practice (Tarantola et al. 1997; Young and Marteniuk 1998) and long-term training (Marin et al. 1999). Each of these self-generated influences improve postural performance by shifting control to a more automatic, feedforward manner in which the number of possible control strategies is greatly reduced. Thus, feedback information can be used for fine-tuning movement execution.

Classical ballet is an athletic endeavor which demands high level balance skills as well as precise and efficient movement execution. In addition, both artistic and biomechanical constraints are placed on the success of the performance. Therefore, it is reasonable to assume that dance training has some effect on the postural strategy chosen by the central nervous system to prevent postural instabilities that arise as a result of volitional movement. Indeed, Mouchnino et al. (1992) have shown that dancers employ a unique postural strategy different from naïve subjects when executing a voluntary lateral leg lift. Vertical trunk orientation and COM displacement was managed through feedforward rotation of the pelvis. Novice controls, on the other hand, responded with an inclination of the trunk away from the lifting leg that was temporally coupled with movement onset. However, there were several inherent limitations in this study. First, the task was executed in only one direction. In real life situations, balance is challenged by volitional movements which are performed in a multitude of directions. Also, postural response strategies have been shown to be sensitive to perturbation direction (Henry et al. 1998b; Hughey L.K. and Fung J. 2003). Second, only data pertaining to movement in the frontal plane were analyzed. Human movement, however, is the result of complex patterns of coordinated segmental displacement in three dimensions. Postural responses to internal or external stimuli are not confined to the primary plane of action.

Therefore, the aim of the present study was to quantify and contrast three-dimensional postural responses to multi-directional fast leg lifts in classical ballet dancers and control subjects who are matched by age and body anthropometry. We hypothesize that, regardless of perturbation direction, the anticipatory postural adjustments associated with leg lifting is similar between the two groups. However, important differences will exist in the kinematic strategies employed to maintain balance and equilibrium. We believe that because of classical training, dancers will maintain vertical trunk and head posture while non-dancers will use displacement of the trunk to generate movement or to facilitate maintenance of the required postural orientation.

4.3 Material and methods

4.3.1 Subjects

A convenience sample of eleven healthy female classical ballet dancers and nine active young women without any known neurological or motor deficits participated in this study. All dancers had a minimum of eight years of classical ballet training and were currently attending a minimum of two ballet classes per week. The control subjects all participated in some level of physical activity from karate to basketball but had no formal classical dance training. The dancers and control subjects were matched by age (mean 24 ±6 yrs vs 26 ±7 yrs, $P>0.05$), weight (mean 53 ±5 kg vs 57 ±17 kg, $P>0.05$), and height (mean 162 ±5 cm vs 163 ±5 cm, $P>0.05$). Subjects gave their informed consent according to the procedure approved by the institutional ethics committee.

4.3.2 Apparatus

Subjects stood on two adjacent AMTI OR6-7 force platforms embedded in the floor. The triaxial forces and moments from the platforms were acquired at 1080 Hz. The resultant center of pressure (COP) was calculated as the weighted sums from the individual anteroposterior (A/P: COP_x) and mediolateral (M/L: COP_y) components computed by dividing the respective M/L and A/P moments with the loading force at each force plate (Henry et al. 1998a).

Three-dimensional (3-D) position data from thirty five retro-reflective markers placed over anatomical landmarks were captured at 120 Hz by a six-camera VICON 512 system (Oxford Metrics Ltd.). Marker placement is shown in Figure 4.1A. A biomechanical model (Plug In Gait, Oxford Metrics Ltd.) was used in conjunction with kinematic data and anthropometric measures (height, weight, leg length and joint widths) to define body segments, joint angles and calculate total body COM. All kinematic data were filtered with a 10-Hz low pass, second-order Butterworth filter, based on a residual analysis performed prior to the experiment.

Bipolar Ag-AgCl disposable surface electrodes (Blue Sensor) were applied over the muscle bellies of four right-sided agonist-antagonist muscle pairs: ankle – tibialis anterior (TA), gastrocnemius medialis (MG); knee – rectus femoris (RF), semitendinosis (ST); hip – adductor (AD), tensor fascia latae (TFL); and trunk – rectus abdominus (RA), erector spinae at the L_3 level (ES). Electromyographic (EMG) signals were recorded at a sampling rate of 1080 Hz by an 8-channel TELEMG system (BTS), after full wave rectification, amplification and band-pass filtering (10-400 Hz low-pass). The EMG signals were further low-pass filtered at 100 Hz during off-line analysis based on a previous residual analysis.

4.3.3 Procedure

The initial stance position is illustrated in Figure 4.1A. All subjects stood barefooted, with heels touching and oriented in a 45° toe-out position. This foot orientation was chosen as a compromise between the extreme 90° and 10° toe-out stance postures that are comfortably maintained by dancers and non-dancers, respectively. Each foot was placed on an individual force plate (AMTI OR6-7). Arms were abducted to shoulder height with elbows and wrist slightly flexed. Gaze was held straight ahead. Subjects were instructed to maintain this initial posture throughout the experiment.

Following an audio signal, subjects were required to lift either their right or left leg in one of five directions (front, side, back, 45° front diagonal or 45° back diagonal, Figure 4.1B) to a height corresponding to an inter-leg separation angle of 45°. Subjects were instructed to perform the movement as fast as possible, with no flexion of either knee and maintain the final leg position for a minimum of 3 seconds. Subjects were given a practice session prior to recording. The choice of swing leg and lift direction were randomized within test blocks (i.e. one lift in each of the ten directions). Subjects completed five test blocks for a total of 50 trials.

4.3.4 Data processing

All data were adjusted to movement onset as defined by the point at which the vertical velocity of the lateral malleolus marker of the lifting leg exceeded twice the standard deviation of its background value (Mouchnino et al. 1992). Data were then divided into three time intervals: the anticipatory, movement and maintenance phases (Figure 4.1C & 4.1D). The start of the anticipatory phase was indicated by the first change in COPy (M/L) velocity exceeding twice the standard deviation above its background value (Mouchnino et al. 1992). The maintenance phase was set as the 1000 ms period after which the vertical velocity of the lateral malleolus marker had slowed to 0 ± 5% of its maximum value. Due to the electromechanical delay between muscle activation and force generation, for EMG analysis, each phase was shifted 30 ms earlier with respect to the kinematic time intervals. An example of the three time intervals are shown in Figures 4.1C (non-dancer) and 1D (dancer). After the initial practice session, no main effects between groups were found for either leg lift height ($F_{[1,18]} = 0.02$; $P>0.5$) or leg lift velocity ($F_{[1,18]} = 2.61$; $P>0.1$). Therefore, to facilitate comparison between the two groups, data from the anticipatory and movement phases were normalized over time to 100% of each phase.

Three-D kinematic analysis of the head, trunk and pelvis segments was performed. The head, trunk and pelvis were each modeled as a plane described by four markers: head – R/L mastoid and R/L temple; trunk – upper and lower sternum, C_7 and T_{10}; and pelvis – R/L anterior- and R/L posterior-superior iliac spine (Figure 4.1A). For each plane, a normal vector, perpendicular to the plane and originating from the center of the bisecting lines joined by the four markers, was computed. Three-D segmental angular excursions for the head, trunk and pelvis were determined from deviations of each normal vector from the global axis system (Figure 4.1A). Positive angular changes corresponded to forward rotations in the sagittal plane, left tilts in the frontal plane and left rotations in the horizontal plane. Also, knee and elbow joint flexion angles were calculated based on angular differences between the adjacent thigh/shank and upper-arm/forearm segments, respectively. Full extension at these joints corresponded to a flexion angle of 0°.

In addition, three-dimensional segmental coordination patterns of the head trunk and pelvis were evaluated by means of principal component analysis (PCA). For each trial of each subject, a covariance matrix **R**, containing the mean centered time-varying angular displacements of each variable in each plane, was calculated (total of nine variables). PCA was used to determine the rank-ordered eigenvectors, $u_1 - u_9$ and associated expansion coefficients of **R** that corresponded to the orthogonal directions of maximum variance in the data set. Coordination patterns were assessed by using the first two eigenvectors since on average they explained 99% of the total variance (see Table 4.2).

Peak-to-peak displacements, defined by the difference between minimum and maximum displacement values, were calculated for COP, COM and the kinematic variables. In addition, total "sum of the squares" excursions were determined for the COP (2D) and COM (3-D) for the entire trial as well as for each time integral. Data from different trial blocks for each individual were ensemble-averaged across direction. These averages were then pooled to produce a population average.

Muscle latencies were defined as the first burst which exceeded a threshold of two standard deviations above background signal and lasting at least 25 ms (Henry et al. 1998b). A muscle must have a firing probability of at least 60% (activated 3 out of 5 trials) to be considered a dynamic postural response. After filtering the data at 10 Hz, the mean integral of each muscle response was determined by integrating the area under the EMG response curve for the anticipatory, movement and maintenance phases. Next, the data were normalized to the maximum response for each muscle regardless of leg lift direction. Then, the data from each subject were averaged so that a group profile could be determined. Since each subject was instrumented only on the right side, EMG responses were termed "swing limb EMG" during right leg lifts and "stance limb EMG" during left leg lifts.

A mixed two-way repeated measures model of analysis of variance was used to determine any significant main effects due to group (dancer vs non-dancer), direction of leg lift (front, R/L diag front, R/L side, R/L diag back or back) or their interaction. A p-value of 0.05 was accepted to be significant. When indicated, post-hoc pairwise comparisons were made following a Bonferroni adjustment for multiple comparisons.

4.4 Results

In general, dancers executed the desired leg lifts in a smooth and consistent fashion. Non-dancers, as can be seen by the malleolus trace in Figure 4.1C, were not so fluid. In fact, most non-dancers over-shot the final leg position, while dancers reached the end-point in one controlled movement.

4.4.1 Changes in COM and COP

Primary differences between dancers and non-dancers were found for A/P amplitude, but not M/L. For most lift directions, COP movement in the A/P direction was characterized by a three-peak displacement pattern for both groups (Figure 4.2A). However, the magnitude and temporal characteristics differed between the groups. For front, front diagonal and side lifts, the initial forward displacement of the COP occurred before movement onset and, in the case of the dancer group, reached a maximum displacement prior to or at the onset of movement, whereas the maximum for the non-dancer group occurred after movement initiation. In addition, the magnitude of this anticipatory shift was larger for non-dancers (~20 mm vs. 15 mm in dancers). Back and back diagonal leg lifting did not result in the anticipatory forward COP shift for either group. The second, backwards COP shift peaked later for non-dancers (approximately 1/3 vs. 1/4 of the movement phase) and again was of a larger magnitude particularly in the back lift directions where the shift was up to 10 mm greater. The third peak, or "plateau", which began before the end of the movement phase for all lift directions except straight front, occurred earlier in dancers than non-dancers. M/L COP displacement patterns were similar between the two groups. An initial shift towards the upcoming swing limb peaked near movement onset and was followed by a quick shift away from the swing limb. For front leg lifts, the second shift began earlier in the dancers, but this is probably due to differences in movement execution.

Peak-to-peak COM and COP displacements are shown in Figure 4.2C. A group main effect was found for COP displacement in the A/P direction ($F_{[1,18]} = 9.64$; $P<0.01$), but no group vs direction interaction. The non-dancer group demonstrated a larger A/P COP shift than the dancers. Also, a main effect due to group ($F_{[1,18]} = 10.92$; $P<0.005$) and an interaction due to group and direction ($F_{[7,126]} = 4.21$; $P<0.001$) were found for the A/P COM displacement. Post hoc comparison confirmed significantly larger displacements in non-dancers only during left and right front diagonal leg lifts. No significant differences between groups were found for M/L COP or COM displacements. A significant interaction effect was observed for vertical COM displacement ($F_{[7,126]} = 4.90$; $P<0.001$), but no main effects (Figure 4.2B). Dancers maintained the same vertical COM displacements through all leg lifts whereas the COM height was less than half in non-dancers during a backward leg lift. The total distance traveled by the COM (3-D) and COP (2D) trajectories during the maintenance phase for all leg lift directions is shown in Figure 4.2D. During the maintenance phase, both COM and COP trajectories were shorter and more stable in the dancer group. A significant main effect due to group existed for total x-y-z COM excursion ($F_{[1,18]} =64.47$; $P<0.001$) and x-y COP excursion ($F_{[1,18]} = 16.21$; $P<0.001$). A significant interaction due to group and direction was found for COP excursion ($F_{[7,26]} =2.18$; $P<0.05$), but not for COM excursion. Post hoc comparisons revealed significant differences for diagonal front and left diagonal back lifts. These results suggest that non-dancers have more difficulty maintaining the final lift position, particularly during front diagonal leg lifts.

4.4.2 Changes in head, trunk and pelvis orientation

Figure 4.3A illustrates displacement of the trunk with respect to the pelvis in the sagittal (column 1), frontal (column 2) and horizontal (column 3) planes for left front, side and back leg lifts. Not shown were data from diagonal leg lifts that revealed movement patterns in between those of the front/back and side leg lifts. There was notable discrepancy between dancer and non-dancer axial movements in terms of trunk and pelvis rotations during leg lifts that had sideway and backward components (see middle and lower plots in column 3 of Figure 4.3A). Dancers rotated their trunk and pelvis toward the lifting leg, especially during back leg lift where large pelvic rotation was used to assist the lift. In contrast, non-dancers demonstrated small trunk and pelvis rotations away from the moving leg. During side leg lifts, dancers displaced their trunk minimally in the sagittal and horizontal planes while tilting the pelvis backward in the sagittal plane and toward the lifting leg in the horizontal plane. Non-dancers, on the other hand, rotated the pelvis forward and away from the lifting limb.

The peak-to-peak excursions (mean + SE) of the head (Figure 4.3B, column1), trunk (column 2) and pelvis (column 3) displacements for the sagittal, frontal and horizontal planes are shown in Figure 4.3B. There was a significant main effect due to group for head and trunk excursions in all three planes (Table 4.1). There were no significant interactions for head displacements. As for the trunk, all interactions were significant due to the effects of lift direction on trunk displacement in the non-dancers.

The only case in which the change in trunk orientation was not larger for the non-dancers was trunk rotation during straight back lifts (column 2).

By contrast, significant group differences for pelvis excursions were present in the sagittal and frontal planes, while a major interaction of group and direction occurred in the horizontal plane (Table 4.1 and Figure 4.3B, column 3). Non-dancers displayed larger pelvic excursions than non-dancers in most leg lifts, especially pelvic motions in the plane of leg lift, with the exception of pelvic rotation during back leg lift in which the excursion was much smaller than dancers.

Figure 4.4 and Table 4.2 show the results of the PCA based on the nine kinematic variables (coordination of head, trunk and pelvis movements in the 3 planes). The percentage variance for each variable that was explained by the first two eigenvectors for left-sided lifts is presented in Figure 4.4A. Non-dancers are shown in the first column and dancers in the second. The most striking result is the large contribution of the pelvis to the first principal component for the dancer group, regardless of movement plane, while the trunk was more represented in the non-dancer group. These findings were particularly applicable to back, back diagonal and side leg lifts. This implies that dancers control COM displacement through 3-D adjustments of the pelvis while non-dancers offset the mass of the lifting leg by counter-rotation of the trunk. The kinematic strategy used for front and front diagonal leg lifts was more similar between the two groups. As for the second principal component, for dancers, it was almost entirely composed of head and trunk displacement, whereas for non-dancers, pelvis displacement was also involved. Figure 4.4B illustrates the time course or expansion coefficient of the first two components. The time course for the first eigenvector was comparable between groups, essentially beginning at movement onset and plateauing by the end of the leg lift. The variability of the first expansion coefficient was greater in the non-dancer group, especially during the anticipatory phase and the maintenance phase. The second expansion coefficient, markedly more variable in the non-dancer group after movement onset, was larger and of longer duration. In addition, during side, back and back diagonal leg lifts, the direction of the trace was opposite for the two groups. This is in agreement with the conflicting trunk and pelvis rotations previously described. Overall, the PCA revealed that dancers relied more on pelvis adjustments during fast leg lifting whereas non-dancers utilized trunk displacements.

4.4.3 Intermediary joints

Knee and elbow flexion were present during leg lifting regardless of perturbation direction. Figure 4.5A presents the average group time course of knee and elbow flexion for three leg lift directions. Note the early knee flexion in the stance limb of non-dancers, occurring well before movement onset. During front and side leg lifts, its onset of closely followed anterior COP displacement while during back lifts, the flexion followed anterior COM displacement. Flexion of the swing limb knee began with the focal movement for both groups. However, for non-dancers, the swing limb was more flexed remained flexed throughout the movement and maintenance phases while dancers extended the knee before the end of the movement phase. This was observed in all leg lifts except back leg lifts in which the swing knee remained slightly (~10°) flexed. The peak-to-peak (mean + SE) knee flexion magnitude is shown in Figure 4.5B. There was a significant main effect due to group and a significant interaction effect due to group and direction for knee flexion in both the stance ($F_{[1,18]}$ = 21.79; P<0.001; $F_{[7,26]}$ = 2.12; P<0.05) and swing ($F_{[1,18]}$ = 31.20; P<0.001; $F_{[1,18]}$ = 3.72; P<0.005) limbs. Post hoc comparisons showed that non-dancers executed significantly larger knee flexions for all leg lifts except during straight back lifts for the stance limb and during right side and right back diagonal lifts for the swing limb. When significant, knee flexion of the stance limb was nearly twice as large for non-dancers as compared to dancers. On the swing leg, the differences were even greater. Overall, due to the increased amount of stance limb knee flexion used by the non-dancer group, a significant difference between the groups in terms of vertical COM displacement might be expected. However, only back leg lifting produced a significant vertical COM difference. Interestingly, back is the only lift direction in which knee flexion was not different between dancers and non-dancers. These findings suggest that the vertical displacement of the COM is more related to the greater trunk displacement used by non-dancers.

Flexion at the elbow joint (Figure 4.5A) occurred concurrently with the onset of leg lifting. The only significant difference between groups was seen in the stance side elbow ($F_{[1,18]}$ = 12.39; P<0.005) which flexed twice as much as compared to dancers (Figure 4.5B). This elbow flexion might be related to the larger degree of trunk motion exhibited by non-dancers towards the stance limb.

4.4.4 EMG responses

No statistically significant differences were found between the two groups with regards to anticipatory muscle activation latencies. As we have previously observed, activation of the shank muscles always preceded activation of the muscles deemed the "prime movers" (Hughey L.K. and Fung J. 2003). In addition, RA, TFL and ST muscles were not consistently activated during the anticipatory phase by subjects in either group.

Figure 4.6 illustrates the EMG integrals during the anticipatory, movement and maintenance phases for the eight instrumented muscles (see methods). Overall, the magnitude of EMG muscle activation during the anticipatory phase was negligible in the dancer population as compared to the non-dancer group for all muscles tested ($P<0.005$). The only muscle to demonstrate a significant interaction effect was RF ($F_{[7,26]} = 4.65$; $P<0.001$) in which the magnitude of response in the swing limb was larger in non-dancers for all directions of leg lifts except side lifts. The increase in muscle activation found for the stance limb knee and hip muscles in non-dancers might well be related to the anticipatory knee flexion demonstrated.

During the movement phase, a significant main effect due to group was found for ST ($F_{[1,7]} = 7.64$; $P<0.05$). However, all muscles showed a significant interaction due to group and leg lift direction ($P<0.05$). Post hoc comparisons illustrated important differences in activation patterns particularly for MG, RF, TFL and RA. During side and diagonal front leg lifts, dancers activated the swing leg MG more than non-dancers. Since dancers typically plantarflexed the lifting foot, particularly in the early stages of the lift, this is not surprising. As for RF, dancers showed greater activation on the swing leg during side lifting as compared to non-dancers who used the RF more on the stance side during side lifting. Both the TFL and RA showed a higher degree of directional sensitivity in activation pattern for dancers versus non-dancers. For dancers, TFL was maximally active on the swing limb during back diagonal leg lifts. The magnitude of RA response for dancers on the swing leg side was greatest during side, diagonal back and back lifts. This tuning was also observed in the swing limb ES, which was maximally activated during back and back diagonal leg lifts. This concomitant activation of the abdominal and back muscles may have served to control trunk displacement in the dancers. Non-dancers did not demonstrate any modulation of RA and ES response was less finely tuned than for dancers.

In general, muscle activity during the maintenance phase was simply an amplification of the previously described patterns. Important to note is the increase in stance limb ankle and knee activations in the group of non-dancers. Non-dancers appear to stiffen the support limb while controlling balance. As well, EMG response in dancers was more directionally tuned as compared to non-dancers.

4.5 Discussion

The aim of this study was to characterize the postural responses of skilled ballet dancers and athletic non-dancers in the task of multi-directional leg lifting. The task is adapted from a common practice maneuver from the classical ballet repertoire in which leg lifts are generally performed in the pure front, back and side directions. The experimental protocol enabled us to assess the effects of classical ballet dance training on balance strategies and coordination patterns, and generalize them to the effects of long-term task-specific motor learning and endurance training.

4.5.1 Regulation of COM positioning by COP adjustment

COM control is of paramount concern during any voluntary movement since changes in body orientation lead to potentially destabilizing changes in the location of total body COM. To avoid falling, controlled acceleration of the COM must be produced (Pai and Patton 1997), most likely in a feedforward manner (Pai et al. 2003). In our study, both dancers and non-dancers were able to coordinate the control of COM displacement with the required leg lift. We observed differences between groups with regards to displacement magnitude only during diagonal front lifting which resulted in larger A/P displacements in non-dancers and during back lifting which led to decreased vertical displacements for non-dancers. Mouchnino et al. (1992) previously reported that dancers, as compared to naïve subjects, were better able to minimize lateral COM displacement during side leg lifting while the magnitude of A/P COM displacement was similar between the two groups. There are several explanations for this discrepancy. First, the initial base of support (see Figure 4.1) was slightly different in the two studies (feet parallel vs 45° toe-out). It is likely that the 45° toe-out base of support adopted in our study facilitated lateral displacement of the COM while compromising longitudinal motion. Also, our subjects were not prevented from making arm motions. Instead, they were able to make subtle arm adjustments which might directly influence COM changes. During leg lifting in any direction, non-dancers reduced the length of the arm on the supporting limb side through flexion at the elbow joint. Since we also found more than two-fold increase in frontal plane trunk rotation for non-dancers, but no significant group differences with respect to M/L COM changes, we believe that elbow flexion could well contribute to the reduction of lateral COM displacement. If we consider the timing of A/P COM displacement, in general, the initial changes occurred earlier, were of a shorter duration and smaller magnitude in dancers as compared to non-dancers. Also, the total distance traveled by the COM during the maintenance phase was smaller, regardless of lift direction. As for vertical COM control, although non-dancers demonstrated a smaller vertical increase than dancers for back leg lifts, the difference can be explained by the large magnitude of forward trunk motion used by non-dancers to offset expected challenges to A/P COM positioning. Therefore we agree with Mouchnino et al. (1992) that dancers were better able to control COM displacement than non-dancers and the conclusion holds true regardless of the direction of leg lifting.

One means by which COM control can be achieved is through COP adjustment (Winter et al. 1998). In our study, evidence of COM control by COP shifting was seen in both groups. However, similar to Mouchnino et al. (1992), we found the responses to be more efficient and less perturbing in dancers. Consider the anticipatory forward COP shift which was evident in all forward leg lifts. This anticipatory COP change has been recorded in activities which involve displacement of one of the support limbs and is used to generate thrust for the upcoming movement (Rogers and Pai 1990). In our study, the magnitude of the initial thrust peak was smaller and its duration shorter in the dancer group, thus reducing its effect on COM. Moreover, we also found a low magnitude of high-frequency COP oscillations during position maintenance in dancers (see Figures 1C & 1D), as reported earlier by Mouchnino et al. (1992) for lateral leg lifts. Hugel et al. (1999) reported similar results with respect to postural control during unperturbed quiet stance. They suggest that dancers are more aware of segmental orientation with respect to the vertical gravity axis than non-dancers and that the reduced sway area associated with dancer response means that dancers are more precise in their control. Indeed, this was illustrated in our study by the consistent, smooth vertical displacement of COM as weight support was transferred from two feet to one foot (Figure 4.2B).

4.5.2 Influence of leg lift direction

Leg lift performance by non-dancers seemed to be affected by the stance limb being the dominant or non-dominant leg in daily activities. Classical dance training stresses the concept of movement symmetry. All dance steps or combinations of steps are practiced on both the right and left. Although most dancers profess a preference for one limb or the other for support, our results support the idea that during simple dynamic balance tasks like fast leg lifting their performance capabilities are not hindered by stance limb selection. The same cannot be said for non-dancers as shown by swing limb knee flexion or by total COP excursion where left diagonal back leg lifts were more destabilizing than right diag back leg lifts. Individuals who have not trained for movement symmetry, demonstrate dominance of one limb over the other. The concept of leg dominance has been shown in activities ranging from bicycle pedaling to locomotion (Arsenault et al. 1986; Smak et al. 1999). Prior to data collection, each of our subjects were asked which foot they would use to kick a ball or with which foot they began stair climbing. All subjects claimed the right leg as the preferred moving limb. Therefore, it is not surprising that for the most part, differences between the two groups were more apparent when the left leg was lifted. Left leg lifting represented a task which the non-dancers had not practiced.

Front leg lifting was the one direction in which the greatest degree of symmetry was observed between the two groups. This is not surprising when front leg lifting is an integral activity of many tasks in everyday life. Gait initiation, stair climbing, even getting into the shower, involves front leg lifting. However, none of these tasks require a straight knee as in our paradigm. We asked our subjects to maintain a straight leg throughout each lift, but the non-dancers were unable to comply (Figure 4.5). In fact, knee flexion was an active component in the non-dancer movement strategy. The energy and torque required to lift the full limb was reduced by the shortening of the lever arm.

4.5.3 Head, trunk and pelvis coordination

Activities such as skating, gymnastics or dance, which require not only athletic prowess but also precise movement execution, have been shown to impose constraints on postural coordination. That is, due to the kinematic rules exacted by the discipline, natural response strategies are compromised. Marin et al. (1999) examined postural changes during head tracking in gymnasts and non-gymnasts and found that expert gymnasts maintained an ankle-type balance strategy longer than lesser trained gymnasts. Since gymnasts are penalized for hip displacement, the researchers concluded that expertise led to modification of coordination strategies.

In the case of classical ballet, we expected highly trained dancers to strive to maintain vertical head and trunk orientation during multi-directional leg lifting. From an early age dancers are taught to move their lower and upper body segments independently from a more or less vertical support base, i.e. the trunk. On the other hand, based on an earlier study, we expected non-dancers to use changes in trunk orientation 1) to control COM positioning and 2) to facilitate leg lifting (Hughey L.K. and Fung J. 2003). Mouchnino et al. (1992) have reported just such a relationship for frontal plane kinematics between dancers and naïve subjects during lateral leg lifts. Our three-dimensional kinematic study extends this work and provides a more complete description of the changes in postural strategy incurred through training in classical ballet.

We found significant differences between the dancers and non-dancers in terms of angular changes in head, trunk and pelvis orientation. The magnitude of head displacement, for instance, was twice as large in non-dancers versus dancers for all lift directions and in all planes. Also, the variation between individual non-dancers was quite large. Thus, we suggest that non-dancers were not able to maintain vertical head orientation as well as classically trained dancers. Another important result that could not be made possible without kinematic analyses in three planes is that for some leg lift directions dancers and non-dancers displaced the trunk and pelvis in opposing directions (Figure 4.3A). This is particularly true of angular displacements in the horizontal plane.

Classical dancers are trained to maintain a certain degree of external limb rotation which facilitates leg lifting by releasing tension in the ligaments surrounding the hip joint. During a side leg lifting, dancers rotated the pelvis and, to a lesser degree, the upper-trunk towards the lifting leg while activating the swing limb TFL, thus essentially stiffening the pelvis area and reducing COM displacement. Non-dancers twisted around the vertical axis and used RF to maintain swing leg positioning. Without a 3-D analysis, this mechanistic explanation would not be revealed.

Differences between dancer and non-dancer lift strategies are clearly evident following PCA of the nine kinematic variables (Figure 4.4). Immediately apparent is the significant use of the pelvis in the first principal component (PC) by dancers and the reliance on trunk displacement by non-dancers. Since the rising edge of the first PC coincided with movement onset and peaked near the beginning of the maintenance phase, we considered it to contribute to movement production. Both groups were fairly consistent in their use of the first PC, although for the most part, dance response was smaller and of shorter duration. In addition, variation between individual dancer responses was smaller than that of non-dancers. The second PC peaked near the middle of the movement phase and in the case of non-dancers continued to oscillate throughout position maintenance. Thus, we deem the second PC to be responsible for movement deceleration and subsequent postural control. Non-dancers had more difficulty controlling ballistic leg lifts than dancers as is clearly demonstrated by the magnitude of the second PC as well as the large standard error. Interesting to note is the contribution of the horizontal pelvis displacement to the second PC for dancers. This supports our previous proposition that dancers utilize horizontal pelvis rotation to control single limb stance. Therefore, we believe that dance training has narrowed the kinematic strategy with respect to multi-directional leg lifts to a very specific set of angular displacements which focus on adjustments at the pelvis.

Both the "pelvis strategy" employed by dancers and the "trunk strategy" used by non-dancers achieve the goal of COM control (see Figure 4.2). However, over the long run, the pelvis strategy is more efficient and more stable. By rotating the trunk away from the lifting leg, non-dancers rely on the mass of the trunk to offset any disturbances to COM positioning which are caused by the mass of the moving leg. Since the trunk comprises two-thirds of the total body mass, anticipatory displacement of the trunk is potentially even more destabilizing than the actual leg lift. Thus, both trunk and leg generally move in tandem. As was shown by Figure 4.6, more energy is required to control both leg and trunk positioning. The minimization of trunk displacement exemplified by dancers simplifies COM control by reducing the need for large post-movement adjustments. In addition, pelvis rotation can precede focal movement without endangering postural stability and thus significantly reduce balance perturbations that are generated by the focal movement.

4.5.4 Effects of training on muscle activation patterns

In both groups, anticipatory muscle activation latencies were similar and followed a distal to proximal pattern. Although we did not find any significant differences between classical dancers and non-dancers, anticipatory trunk muscle activation was inconsistent in dancers. In fact, if dancers used RA or ES at all, it was late into the movement phase or during position maintenance. Non-dancers, on the other hand, activated all the muscles tested in anticipation of the upcoming movement regardless of lift direction, thereby stiffening the ankle, knee and hip joints. Patla et al. (2002) examined the effects of voluntary arm movements on anticipatory postural responses. By comparing experimental data with an inverted-pendulum model, they found that joint stability was actively controlled by the central nervous system prior to the onset of movement whereas COM positioning was due to passive feedback-type control. It is plausible that in our study, non-dancers activate the muscles in an attempt to prevent undue segmental displacement whereas dancers perform leg lifts in a feedforward manner and require little if any preventative action.

Since we evaluated postural responses for leg lifts in multiple directions, we were able to uncover a directional specificity in muscle activation pattern which was more finely tuned for dancers as compared to non-dancers (see Figure 4.6), particularly for the more proximal postural muscles. These data suggest that through training, classical dancers have developed a series of task specific postural strategies which involve activation of a minimal number of muscles. Similar findings have been reported by Debu and Woollacott (1988). They compared muscle responses to surface translation in untrained children and children with gymnastics training. As with our study, no differences in leg muscle activations were found between the groups, although the response of the upper trunk muscles were more flexible. These results led the researchers to conclude that training leads to subtle changes in postural control. The absence of group differences for anticipatory muscle activation in our study may be due to the choice of instrumented muscles rather than a true lack of difference. It is conceivable that anticipatory muscle activations may differ between dancers and non-dancers in the postural muscles of the hip, pelvis and trunk which are used to stabilize the support base prior to leg lifting. Since many of these are deep set muscles, our choice of surface EMG was an inappropriate tool for measuring their activity. Pedotti et al. (1989) have also reported differences in EMG activation patterns between gymnasts and controls. They found an anticipatory activation of the lower limb muscles which was present in both groups during forward bending, but was absent from the control group during backward bending. They suggest that forward bending represents a task which has been practiced from a very early date in everyday life and thus is dealt with in a feedforward manner. Backward bending, on the other hand, is not a generally acquired skill and thus requires feedback information. We found similar results with respect to front leg lifting as compared to leg lifting in other directions. The performance strategies employed by trained dancers and non-dancers were most alike during front leg lifts and became more disparate as the lift moved toward the back. A significant difference was found in A/P COP displacement in which front and front diagonal lifting resulted in larger forward displacement. This can be explained by the fact that when non-dancers practice forward leg lifts it is most often in conjunction with the intention of forward progression as in locomotion.

4.5.5 Conclusions

In conclusion, principal component analysis verified our belief that dancers and non-dancers would use different kinematic strategies to both execute the lift and maintain the final posture. In particular, our hypothesis that dancers would maintain vertical head and trunk orientation independent from lift direction while non-dancers would compromise trunk verticality was confirmed. Trunk stabilization in space, as used by dancers, proved to be a better control strategy as was demonstrated by the tuning and amplitude of muscle activation patterns. Non-dancer displacement of the trunk for movement generation and COM stabilization required larger, less focused bursts of activity. Thus, energy output, at least in terms of muscle activation, was minimized through dance training. Therefore, we conclude that through high level training, ballet dancers have learned to perform multi-directional leg lifts in a well-defined, cost effective way.

4.6 References

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4.7 Tables & Figures

Table 4.1 F-values for changes in head, trunk and pelvis orientation.

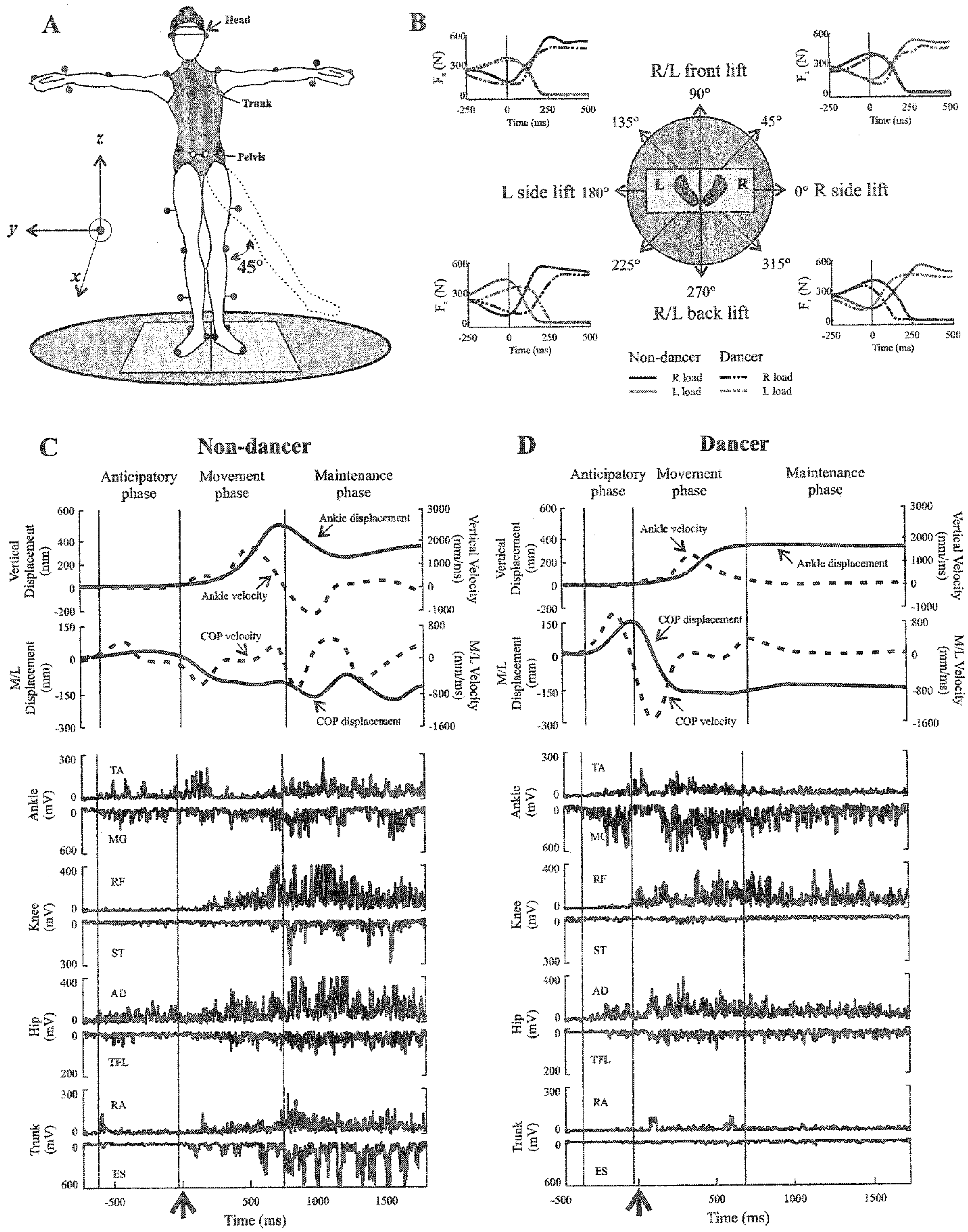
		Main group effect $F_{[1,8]}$	P <0.05	Group vs direction $F_{[7,26]}$	P <0.05
Head					
	sagittal	5.06	*	0.42	NS
	frontal	30.91	*	1.47	NS
	horizontal	12.77	*	1.28	NS
Trunk					
	sagittal	90.72	*	18.54	*
	frontal	115.99	*	3.24	*
	horizontal	28.09	*	2.65	*
Pelvis					
	sagittal	9.74	*	2.63	*
	frontal	2.63	*	4.79	*
	horizontal	1.38	NS	17.04	*

* - statistically significant; NS – not significant

Table 4.2 Eigenvalues and percent variance captured by the first two principal components for changes in three-dimensional head, trunk and pelvis orientation.

	Non-dancers				Dancers			
	PCA #	Eigenvalue of Cov(X)	% Variance Captured this PC	% Variance Captured Total	PCA #	Eigenvalue of Cov(X)	% Variance Captured this PC	% Variance Captured Total
R side	1	141.02	98.75	98.75	1	62.71	98.07	98.07
	2	1.10	0.77	99.52	2	0.98	1.53	99.60
R diag front	1	70.29	95.69	95.69	1	43.20	97.09	97.09
	2	2.14	2.91	98.61	2	0.80	1.79	98.89
R front	1	78.84	97.06	97.06	1	38.29	96.40	96.40
	2	1.76	2.17	99.23	2	0.91	2.29	98.68
L front	1	72.76	95.25	95.25	1	37.21	96.49	96.49
	2	2.68	3.51	98.76	2	0.68	1.76	98.25
L diag front	1	58.69	94.35	94.35	1	46.09	96.57	96.57
	2	2.30	3.70	98.04	2	1.18	2.48	99.05
L side	1	130.22	98.36	98.36	1	67.08	98.09	98.09
	2	1.47	1.11	99.47	2	1.03	1.51	99.60
L diag back	1	198.09	98.04	98.04	1	134.57	99.21	99.21
	2	2.27	1.12	99.16	2	0.75	0.56	99.77
L back	1	166.33	97.14	97.14	1	214.08	99.39	99.39
	2	2.35	1.37	98.51	2	0.72	0.33	99.72
R back	1	212.71	97.86	97.86	1	248.11	99.41	99.41
	2	2.35	1.08	98.94	2	0.93	0.37	99.78
R diag back	1	192.62	98.49	98.49	1	156.18	99.37	99.37
	2	1.37	0.70	99.19	2	0.58	0.37	99.73

Figure 4.1 A) Kinematic set-up with 34 markers. Small circles show reflective marker placement (white circles represent posterior trunk and pelvis markers). The kinematic coordinate system (*x-y-z*) is shown on the side. Leg is lifted to a height corresponding to an inter-leg separation angle of 45°. B) Coordinate system for voluntary leg lifts. Arrow indicates leg lift direction. Insets show loading and unloading forces from a representative dancer and non-dancer (black lines – right force plate; gray lines – left force plate). Solid lines are data from the non-dancer and dashed lines correspond to data from the dancer. C & D) Vertical lateral malleolus displacement/velocity (z-direction), COP displacement/velocity (medial-lateral) and muscle activation during right diagonal front leg lift (45°) for a representative non-dancer (C) and dancer (D). Note: kinematic integrals are offset from EMG by 30 ms.



A
Head
Trunk
Pelvis
45°
B
R/L front lift
90°
135°
45°
L side lift 180°
0° R side lift
225°
315°
270°
R/L back lift
Time (ms)
Non-dancer
Dancer
R load
L load
C
Non-dancer
D
Dancer
Anticipatory phase
Movement phase
Maintenance phase
Vertical Displacement (mm)
Vertical Velocity (mm/ms)
Ankle displacement
Ankle velocity
M/L Displacement (mm)
M/L Velocity (mm/ms)
COP velocity
COP displacement
Ankle (mV)
Knee (mV)
Hip (mV)
Trunk (mV)
TA
MG
RF
ST
AD
TFL
RA
ES
Time (ms)

Figure 4.2 COM/COP. A) Ensemble average COP (thick lines) and COM (thin lines) traces for left leg lifts (right data are a mirror image). First column shows A/P displacements and the second column shows M/L displacements. Dancers are represented by dashed lines and non-dancers by solid lines. Statistical significance at $P<0.05$ is indicated by *. B) Ensemble average vertical COM displacements. C) Total peak-to-peak displacements of the COM and COP for all leg lift directions. Black triangles signify the dancer group (+SE) and gray triangles signify the non-dancer group (+SE). Scale magnitude in the anterior/posterior direction is one-third that for medial/lateral displacement. D) Total distance traveled by the COM (*x-y-z*) and COP (*x-y*) during the maintenance phase. Data are an average of all trials from all subjects. Dancers are shown as black triangles (±SE) and non-dancers are white circles (±SE).

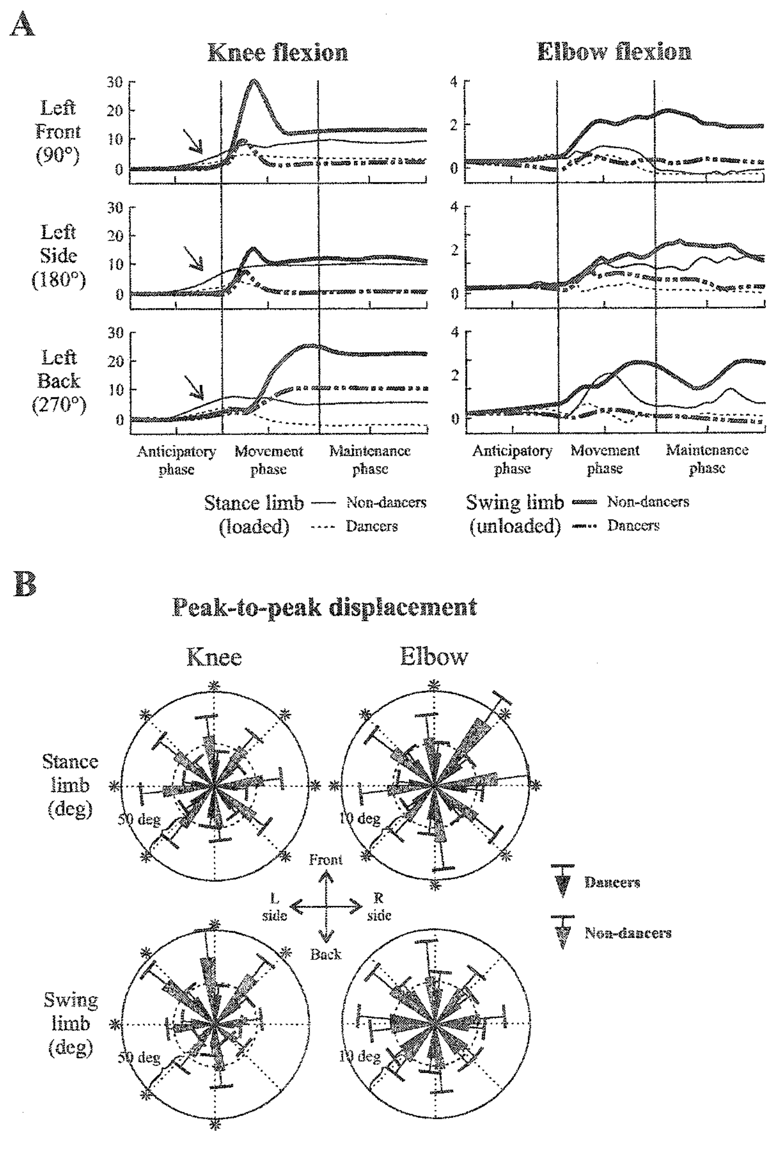
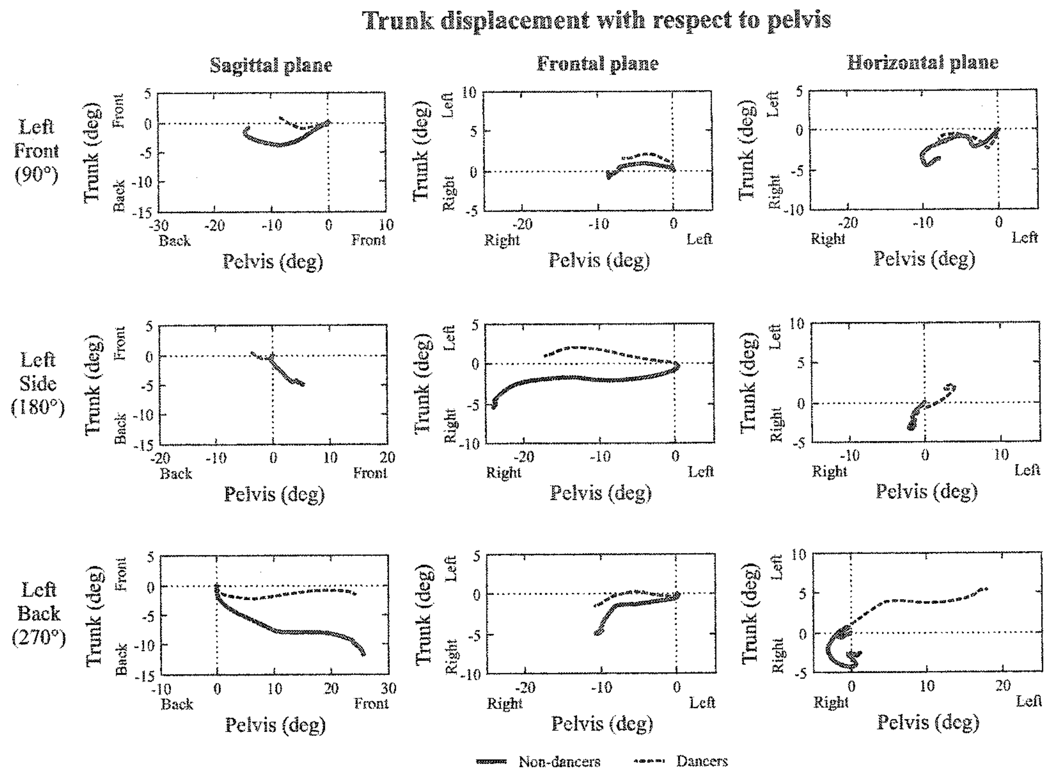

A
Knee flexion
Elbow flexion
Left Front (90°)
Left Side (180°)
Left Back (270°)
Anticipatory phase
Movement phase
Maintenance phase
Stance limb (loaded)
Non-dancers
Dancers
Swing limb (unloaded)
Non-dancers
Dancers
B
Peak-to-peak displacement
Knee
Elbow
Stance limb (deg)
Swing limb (deg)
50 deg
10 deg
Front
L side
R side
Back
Dancers
Non-dancers

Figure 4.3 Head, trunk and pelvis. A) Trunk with respect to pelvis for left front, left side and left back leg lifts in sagittal (column 1), frontal (column 2) and horizontal (column 3) planes. Data represent an average of all subjects. Movement begins at (0,0). Dancers (dashed lines) and non-dancers (solid lines). B) Peak-to-peak head, trunk and pelvis displacement for the three planes. Conventions as described in Figure 4.2.

A


Trunk displacement with respect to pelvis
Sagittal plane
Frontal plane
Horizontal plane
Left Front (90°)
Left Side (180°)
Left Back (270°)
Trunk (deg)
Pelvis (deg)
Front
Back
Left
Right
Non-dancers
Dancers

B

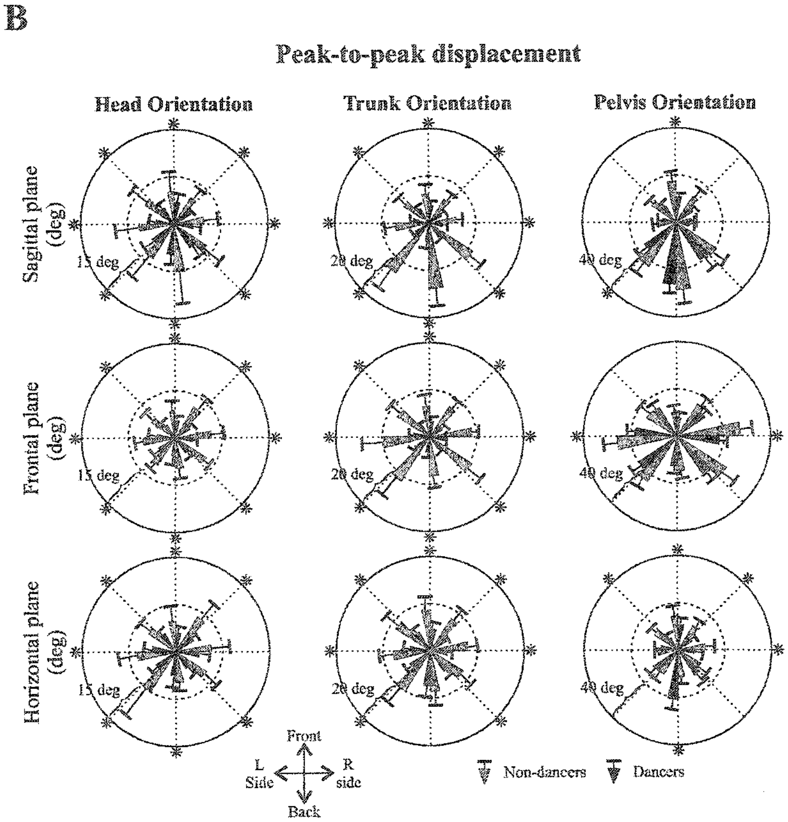

Peak-to-peak displacement
Head Orientation
Trunk Orientation
Pelvis Orientation
Sagittal plane (deg)
Frontal plane (deg)
Horizontal plane (deg)
15 deg
20 deg
40 deg
Front
L Side
R side
Back
Non-dancers
Dancers

Figure 4.4 PCA for head, trunk and pelvis. A) Percentage of the 3-dimensional head, trunk and pelvis angle data which are described by the first two principal components for dancers (right) and non-dancers (left). B) Scaled time course (± SE) of the first two principal components (1st – top graph, 2nd – bottom graph). Variability in the dancer group (dashed line with gray area) versus variability in the non-dancer group (solid line with hatched area).

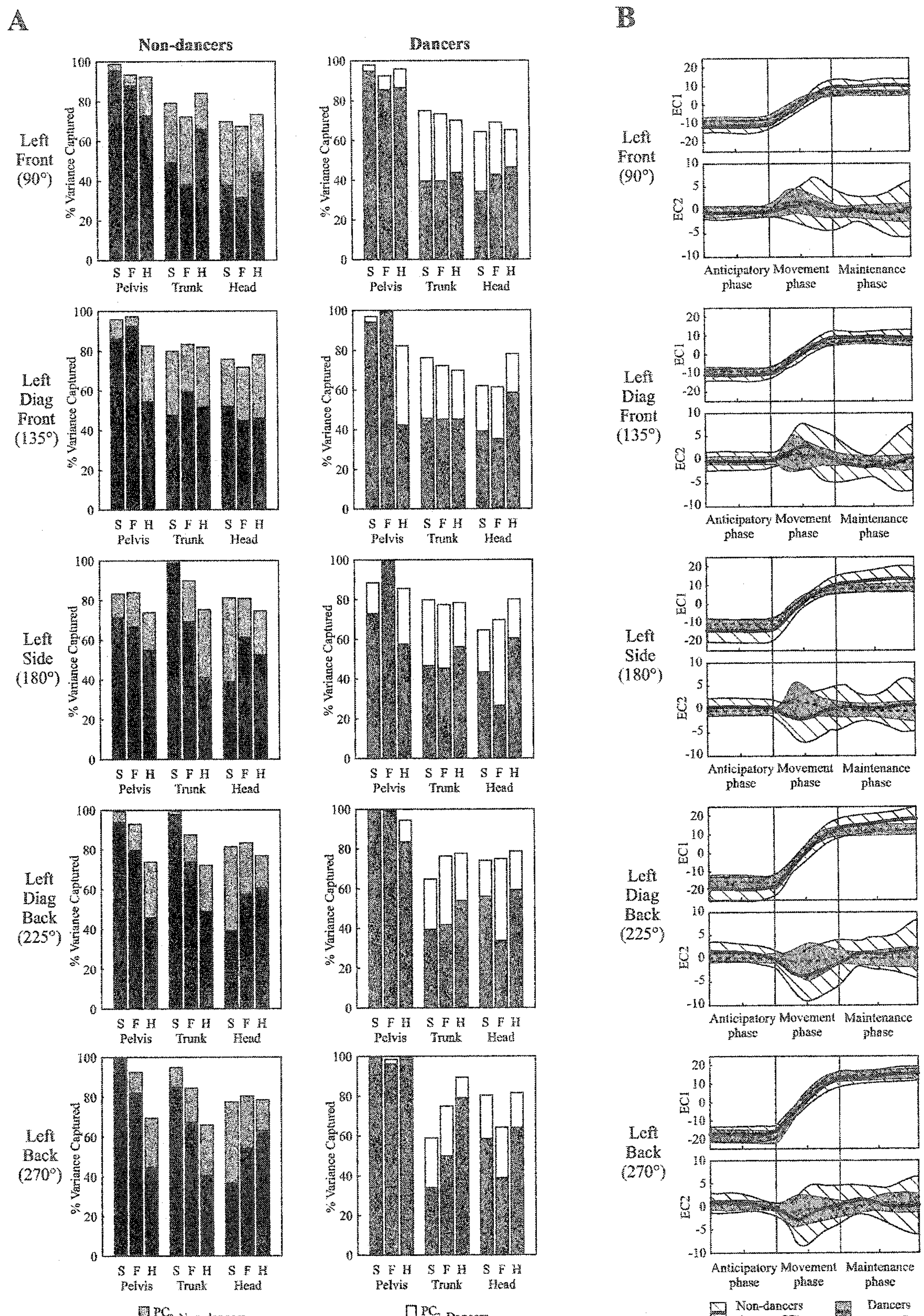
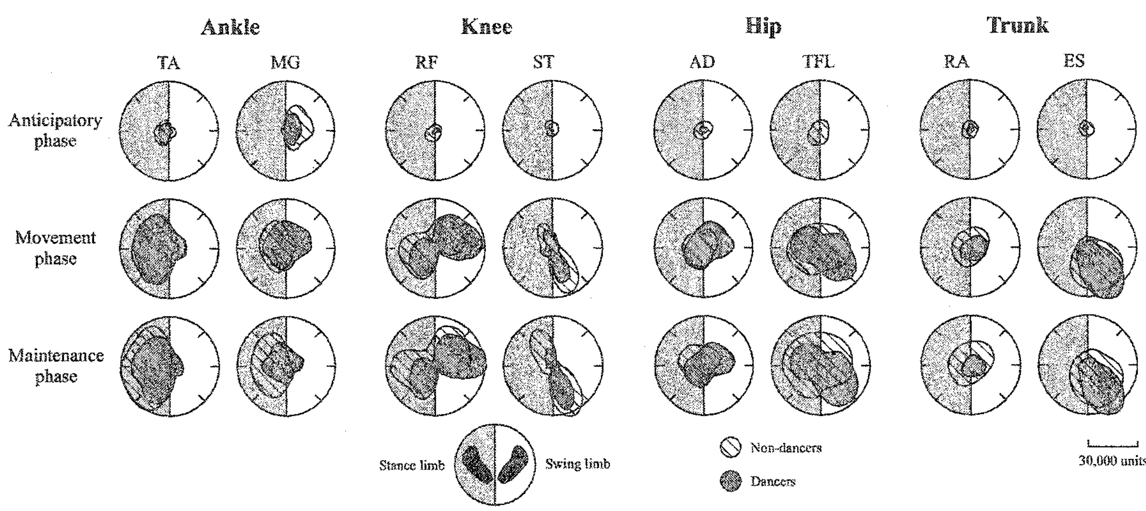
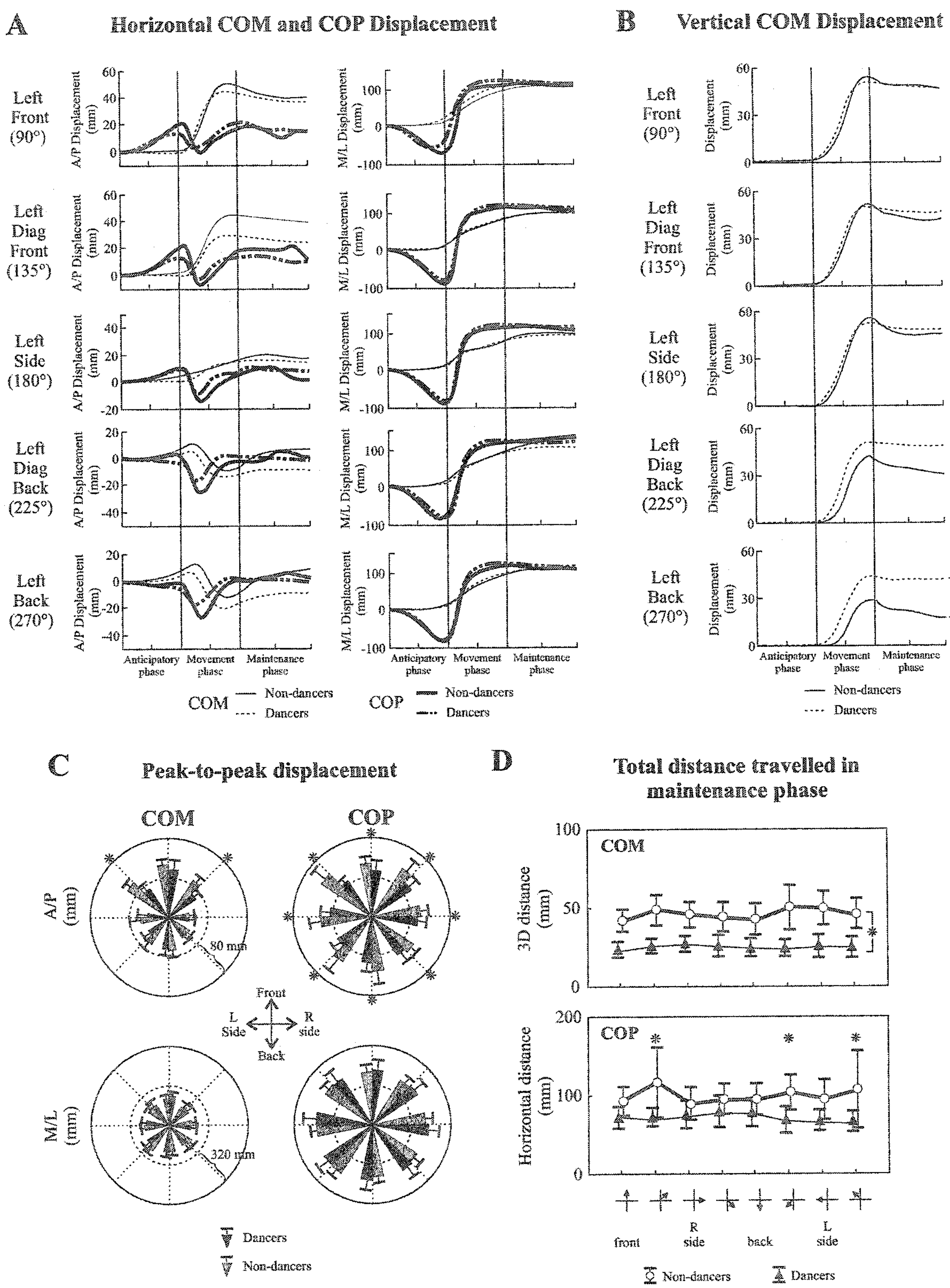

A
B
Non-dancers
Dancers
Left Front (90°)
Left Diag Front (135°)
Left Side (180°)
Left Diag Back (225°)
Left Back (270°)
% Variance Captured
S F H
Pelvis
Trunk
Head
PC2 PC1 Non-dancers
PC2 PC1 Dancers
EC1
EC2
Anticipatory phase
Movement phase
Maintenance phase
Non-dancers (mean ±SE)
Dancers (mean ±S

Figure 4.5 Knee and elbow flexion. A) Knee (left column) and elbow flexion (right column) from average dancer (dashed lines) and non-dancer (solid lines) groups. B) Average peak-to-peak knee and elbow flexion for the loaded (left column) and unloaded (right column) limbs from all subjects over the entire trial.



Ankle
Knee
Hip
Trunk
TA
MG
RF
ST
AD
TFL
RA
ES
Anticipatory phase
Movement phase
Maintenance phase
Stance limb
Swing limb
Non-dancers
Dancers
30,000 units

Figure 4.6 EMG. Muscle tuning curves for four right muscle pairs (ankle – TA,MG; knee – RF,ST; hip – AD, TFL; and trunk – RA,ES). Shaded semi-circle indicates activity when the leg is in stance (during left leg lifts) and white semi-circle indicates activity when the leg is in swing (during right leg lifts). Dancers are gray shaded areas and non-dancers are shown by hatched areas.



A
Horizontal COM and COP Displacement
B
Vertical COM Displacement
Left Front (90°)
Left Diag Front (135°)
Left Side (180°)
Left Diag Back (225°)
Left Back (270°)
A/P Displacement (mm)
M/L Displacement (mm)
Displacement (mm)
Anticipatory phase
Movement phase
Maintenance phase
COM — Non-dancers
---- Dancers
COP — Non-dancers
—·· Dancers
C
Peak-to-peak displacement
COM
COP
A/P (mm)
M/L (mm)
80 mm
320 mm
Front
L Side
R side
Back
Dancers
Non-dancers
D
Total distance travelled in maintenance phase
COM
3D distance (mm)
COP
Horizontal distance (mm)
front
R side
back
L side
Non-dancers
Dancers

Chapter 5 The control of balance in skilled ballet dancers and recreational athletes: II. multi-directional surface tilts

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To be submitted to: Journal of Neurophysiology August 2003

Chapter 4 clearly demonstrated that classically trained dancers and active non-dancers behave differently when performing a voluntary movement for which the dancers have trained. In particular, we found that dancers maintained trunk verticality throughout the multi-directional leg lift task while non-dancers used trunk displacement as a means to offset COM displacement. Both groups were able to perform the focal task, but the strategy employed by the dancers was more efficient as it required smaller segmental displacements. In addition, dancer muscle activation patterns showed sensitivity to the leg lift direction whereas non-dancer response was less finely tuned. But, perhaps most significant, was the use of anticipatory postural adjustments by non-dancers which were noticeably reduced for dancers. Through training, classical dancers have developed the skill to perform fast leg lifts in a smooth, feedforward fashion. Sensory feedback was then used to fine-tune movement performance. These results lead us to the next question, since dance training improves balance performance during a voluntary task, does it also improve balance performance following external perturbation? Several research groups have addressed the effects of dance training on balance and equilibrium during static and dynamic stance (Golomer et al. 1999; Hugel et al. 1999; Perrin et al. 2002). Mixed results have been reported. In one case, dancers were found to perform better than control subjects only when visual integrity is maintained which led the investigators to conclude that the postural improvements seen in the dance population are not transferable to every day situations (Hugel et al. 1999). On the other hand, Mesure et al. (1997) and Golomer et al. (1999) have shown that dancers are less reliant on the visual system to regulate posture than are untrained subjects. In these studies, dancers displayed better balance abilities in all experimental tasks. However, none of these studies addressed the effects that dance training may have on postural control following unexpected balance perturbations. In the following manuscript the postural response strategies of classically trained dancers and active non-dancers to multi-directional surface tilts are compared and contrasted. The results of this study will provide insight concerning the ability to transfer balance strategies from a controlled situation to one in which balance is unexpectedly challenged. My hypothesis is that one common postural control strategy will be used by both dancers and non-dancers. Any differences between the groups will be slight and will include distinctions in segmental coordination patterns which are reminiscent of those found during voluntary leg lifting. If the hypothesis is true and the trained modifications to postural control are carried over then a dance-based rehabilitation program for individuals suffering from balance difficulties can be justified.

5.1 Abstract

Previously we have shown that dancers and non-dancers behave differently during voluntary leg lifting. The current study was designed to assess the effects of high level ballet training on triggered postural responses following multi-directional surface tilting. Classical dancers and active non-dancers were asked to maintain stance while the support surface tilted in one of eight random directions at an amplitude of 10° and a velocity of 53°/s. COM and COP displacements were calculated. In addition, three-dimensional angular changes and segmental coordination patterns for the head, trunk and pelvis were determined. Muscle activation patterns were also examined. Significant differences between groups were found for horizontal COP excursion. Principal component analysis of three-dimensional head, trunk and pelvis orientation revealed differing kinematic strategies. For roll plane and diagonal tilts, the first component revealed that dancers controlled perturbation effects through 3-D rotation of the pelvis combined with horizontal trunk rotation. The later second component was used for stabilization. The principal components for non-dancers were more evenly distributed among variables. Pitch plane tilts produced more similar results between groups with dancers exhibiting a greater contribution from the second component. Early muscle response was dramatically smaller for dancers, whereas non-dancers activated all muscles tested. During balance correction/stabilization, dancer response focused on ankle muscle activation. Non-dancers also used knee, hip and trunk muscles to recover balance. These results support our hypothesis that classical dance training leads to functional adaptations of the postural control strategy associated with triggered postural responses. Dancers are better able to

integrate information from proprioceptive afferents than non-dancers who require head and trunk stabilization to promote visual and vestibular input.

5.2 Introduction

Postural reactions to external disturbances are essential for regaining equilibrium. The central nervous system must quickly convert and regulate sensory feedback into appropriate balance responses to avoid falls. In the laboratory, automatic postural reactions to unexpected perturbations are often produced through displacement of the support surface. These studies have shown that when balance is suddenly compromised, a task specific set of strategies are employed to control posture and equilibrium (Allum et al. 1998; Buchanan and Horak 2001; Schieppati et al. 1995).

Athletic training has a positive impact on balance skills through the resultant build-up of central set reference patterns. Activities such as gymnastics, ice skating or classical ballet, which require not only the accurate but the precise execution of movement, also improve balance and coordination through the development of kinesthetic representation skills (Bringoux et al. 2000; Eloranta 2003; Perrin et al. 2002). That is, through practice, these particular athletes learn to quickly synthesize sensory information which they then are able to apply to an internal body model. Thereby, voluntary movement can be appropriately adjusted for environmental and biological constraints. Hughey et al. (submitted 2003) have assessed the balance abilities of dancers versus non-dancers during multi-directional fast leg lifting and have shown that indeed dancers perform these maneuvers in a smooth concise manner with very little deviation from the intended goal. Non-dancers, on the other hand, do not behave in a uniform fashion and require large postural adjustments not only to perform the focal movement but also to maintain the final segmental orientation. Thus, through high-level training, dancers have either developed new postural strategies for leg lifting or are making better use of existing strategies.

A question then arises concerning the applicability of these adaptations to situations outside of the trained skill set. The particular balance capabilities of classical dancers during stance have been examined by several research groups, but the results have proved inconclusive. Dancers have been found to perform better during quasi-static posturographic testing than untrained subjects only in the presence of vision (Hugel et al. 1999; Perrin et al. 2002) while during specific dance postures (i.e. bipedal demi-pointe or full-pointe), dancers demonstrated no dependence on visual inputs (Hugel et al. 1999). These results led to the conclusion that dance training increased the size of the "task specific" postural control strategy repertoire but did not improve the utilization of pre-existing strategies. On the other hand, Golomer et al. (1999) found dancers to be less dependent on visual inputs than non-dancers during both quiet stance and while balancing on a seesaw board. To explain these results, it was suggested that dancer performance was improved through an increased ability to integrate proprioceptive feedback when visual information was lacking or insufficient for the task. However, none of these studies explored the resultant postural adjustments which follow external balance perturbations. Past research has shown that unexpected surface perturbations produce highly stereotyped muscle activation patterns (Horak et al. 1990; Inglis et al. 1994).

Therefore, the purpose of this study was to quantify and compare the postural response strategies used by dancers and non-dancers to regain balance and equilibrium following unexpected multi-directional surface tilts. We expect to find a common response strategy between trained dancers and non-dancers. If, as has been suggested, dance training improves the use of proprioceptive afferents in the control process then the central control strategy employed by dancers should involve fast directionally sensitive adjustments which occur primarily at the feet and ankles. Non-dancer response will focus on control of head and trunk orientation to promote gaze stabilization (Hughey and Fung submitted 2003). The results of our study will provide important information regarding the pertinence of a dance training program for individuals in which one or more of the sensory modalities has been compromised, such as following stroke, Parkinson's disease or aging.

5.3 Material and methods

5.3.1 Subjects

A convenience sample of eleven healthy female classical ballet dancers and nine active young women without any known neurological or motor deficits participated in this study. All dancers had a minimum of eight years classical ballet training and were currently attending a minimum of two ballet classes per week. The control subjects all participated in some level of physical activity from karate to basketball but had no formal classical dance training. No differences in terms age (mean 24 ±6 yrs vs 26 ±7 yrs, $P>0.05$), weight (mean 53 ±5 kg vs 57 ±17 kg, $P>0.05$), or height (mean 162 ±5 cm vs 163 ±5 cm, $P>0.05$) were found between the groups. Subjects gave their informed consent according to the procedure approved by the institutional ethics committee. These same subjects also participated in a multi-directional leg lift study, the results of which have been presented elsewhere (Hughey L.K. et al. submitted 2003).

5.3.2 Apparatus

Subjects stood on two adjacent AMTI OR6-7 force platforms embedded in the support surface which was mounted over an electro-hydraulically controlled six-degree-of-freedom motion base sevo (Fung and Johnstone 1998). The signals from the force platforms were sampled at 1080 Hz and used to measure ground reaction forces and moments. The resultant center of pressure (COP) was calculated as the weighted sums from the individual longitudinal (COP_x) and mediolateral (COP_y) components of each force plate (Henry et al. 1998a).

Three-dimensional position data from thirty five retro-reflective markers placed over anatomical landmarks were captured at 120 Hz by a six-camera VICON 512 system (Oxford Metrics Ltd.). Marker placement is shown in Figure 5.1A. A biomechanical model (Plug In Gait, Oxford Metrics Ltd.) was used in conjunction with kinematic data and anthropometric measures (height, weight, leg length and joint widths) to define body segments, joint angles and calculate total body center of mass. In addition, four markers were placed on the platform surface so that platform onset could be determined. All kinematic data were filtered with a 10-Hz low pass, second-order Butterworth filter, based on a residual analysis performed prior to the experiment.

Bipolar Ag-AgCl disposable surface electrodes (Blue Sensor) were applied over the muscle bellies of four right-sided agonist-antagonist muscle pairs: ankle – tibialis anterior (TA), gastrocnemius medialis (MG); knee – rectus femoris (RF), semitendinosis (ST); hip – adductor (AD), tensor fascia latae (TFL); and trunk – rectus abdominus (RA), erector spinae at the L_3 level (ES). Electromyographic (EMG) signals were recorded at a sampling rate of 1080 Hz by an 8-channel TELEMG system (BTS), after full wave rectification, amplification and band-pass filtering (10-400 Hz low-pass). The EMG signals were further low-pass filtered at 100 Hz during off-line analysis based on a previous residual analysis.

5.3.3 Procedure

The initial stance position is illustrated in Figure 5.1A. All subjects stood barefoot, with heels touching and oriented in a 45° toe-out position. Each foot was placed on an individual force plate (AMTI OR6-7). Arms were abducted to shoulder height.

Gaze was held straight ahead. Subjects were instructed to maintain this initial posture throughout the experiment.

Upon the experimenter's trigger, the support surface was tilted in the pitch and roll planes. Ten degrees of ramp-and-hold surface tilt in one of eight random axial directions (right/left side unload, toes-up, toes-down, right/left toes-up 45° diagonal and right/left toes-down 45° diagonal) was presented at a peak velocity of 53°/s (Figure 5.1B). The tilt magnitude and speed were sufficient enough to cause a shift from the initial two-footed stance to a single limb (Figure 5.1B). Two catch trials with no surface tilt were included to reduce subject anticipation of upcoming perturbation direction. If it appeared that a subject was attempting to guess the next tilt direction, additional trials or verbal distractions were added. Also, tilt direction was randomized within each test bock and the pattern of perturbation varied between blocks. Subjects completed five test blocks for a total of 50 trials.

Both the voluntary leg lift experiment and the unexpected surface tilt experiment were conducted in a single day to ensure that within-subject comparisons could be made. In addition, each block of leg lifting was followed by a block of surface tilting to reduce any confounding effects due to subject fatigue.

5.3.4 Data processing

All data were adjusted to platform onset as defined by the first visible change of the vertical velocity of the platform marker. The data were subsequently divided into four predetermined time intervals for analysis: 0 to 100 ms from platform onset, short-latency reflex period; 100 to 225 ms, balance correction phase I; 225 to 350 ms, balance correction phase II; and, 350 to 700 ms, stabilizing phase. For EMG analysis, the start of each time phase was shifted 30 ms earlier to accommodate the electromechanical delay between muscle activation and force generation. Note that the short-latency reflex phase was reduced to a 70 ms window. An example of the four time intervals is shown in Figure 5.1C.

Three-dimensional kinematic analysis of the head, trunk and pelvis segments was performed. The head, trunk and pelvis were each modeled as a plane described by four markers: head – R/L mastoid and R/L temple, trunk – clavical, sternum, C_7 and T_{10} and pelvis – R/L anterior- and R/L posterior-iliac spine (Figure 5.1A). For each plane, a vector, orthogonal to the plane and originating from the center of the four markers, was drawn. Three-dimensional angular excursions for the head, trunk and pelvis were determined from deviations of each normal vector from the global axis system (Figure 5.1A). For convenience, forward rotations in the sagittal plane, left tilts in the frontal plane and left rotations in the horizontal plane correspond to positive angular changes. Also, knee and elbow joint flexion angles were calculated based on angular differences between the adjacent thigh/shank and upper-arm/forearm segments, respectively. Extension at these joints is equivalent to a flexion angle of 0°.

In addition, three-dimensional segmental coordination patterns of the head, trunk and pelvis were evaluated by means of principal component analysis (PCA). For each trial of each subject, a covariance matrix $\mathbb{R}$, containing the mean centered time-varying angular displacements of each variable in each plane, was calculated (total of nine variables). PCA was used to determine the rank-ordered eigenvectors, u_1 – u_9 and associated expansion coefficients of $\mathbb{R}$ that correspond to the orthogonal directions of maximum variance in the data set. Coordination patterns were assessed by using the first two eigenvectors since on average they described more than 95% of the total variance (see Table 1).

Peak-to-peak displacements, defined by the difference between minimum and maximum displacement values, were calculated for COP, COM and kinematic variables. In addition, total "sum of the squares" excursions were determined for the COP (2D) and COM (3-D) for the entire trial as well as for each time integral. Data from different trial blocks for each individual were ensemble-averaged across direction. These averages were then pooled to produce a population average.

Muscle latencies were defined as the first burst which exceeded a threshold of two standard deviations above background signal and lasting at least 25 ms (Henry et al. 1998b). A muscle must have a firing probability of at least 60% (activated 3 out of 5 trials) to be considered a dynamic postural response. After filtering the data at 10 Hz, the mean integral of each muscle response was determined by integrating the area under the EMG response curve for the short-latency reflex phase, balance correction phase I, balance correction phase II and the stabilizing phase. Next, the data were normalized to the maximum response for each muscle regardless of surface tilt direction. Then, the data from each subject were averaged so that a group profile could be determined. Since only the right side was instrumented, EMG data from right side unloading surface tilts correspond to limb unloading while left side unloading surface tilts correspond to limb unloading.

A mixed two-way repeated measures model of analysis of variance was used to uncover any significant main effects due to group (dancer vs non-dancer), direction of surface tilt (toes-up, R/L diag 45° toes-up, R/L side-up, R/L diag 45° toes-down or toes-down) or their interaction. A p-value of 0.05 was accepted to be significant. When indicated, post-hoc pairwise comparisons were made following a Bonferroni adjustment for multiple comparisons.

5.4 Results

5.4.1 Changes in COM and COP

An example of center of mass (COM) and center of pressure (COP) displacement during surface tilting is illustrated in Figure 5.1C. In general, COP shifting preceded and exceeded COM displacement (see Hughey and Fung submitted 2003). Both dancers and non-dancers exhibited this behavior.

Figure 5.2A shows the average peak-to-peak displacement of the total body center of mass (COM) and center of pressure (COP) along the anterior/posterior (A/P) and mediolateral (M/L) axes for dancers and non-dancers. Statistical analysis revealed no significant main group effect for either COM or COP. A significant group vs direction interaction was found for A/P COM displacement ($F_{[7,126]} = 2.74$; $P<0.05$). Non-dancers had larger A/P COM displacements during diagonal toes-down and toes-down perturbations, but these results were not statistically significant due to the stringency of the Bonferroni adjustment.

Total three-dimensional excursion of COM (*x-y-z*) and horizontal excursion of COP (*x-y*) over the entire trial (0 to 700 ms) are shown in Figure 5.2B. A significant main group effect for horizontal COP excursion was found ($F_{[1,18]} = 5.89$; $P<0.05$). The total distance traveled by COP was larger for dancers than non-dancers. In addition, the response was more varied between individual dancers.

5.4.2 Changes in head, trunk and pelvis orientation

No significant main group effects were found with respect to changes in head, trunk or pelvis orientation for any of the planes. However, a main group vs direction interaction was found for the pelvis in the sagittal plane ($F_{[7,26]} = 2.12$; $P<0.05$). Further pairwise comparison revealed larger peak-to-peak displacements for dancers during right side unload and right diagonal toes-up surface tilts. However, due to the Bonferroni adjustment, these differences cannot be considered to be significant.

Figure 5.3 and Table 5.1 illustrate the results of principal component analysis (PCA) performed on the three-dimensional head, trunk and pelvis data. Interestingly, as is shown in Table 5.1, excluding pitch plane perturbations, the first principal component for dancers reflected a higher percentage of the total variance as compared to the first component for non-dancers (approximately 94% versus 82% for dancers and non-dancers respectively). The second principal component contributed more to the total variance seen in the non-dancer group than it did for dancers so that the total of the first two components was about equal to the percent variance captured by the first PCA for dancers. However, the outcome of the PCA analysis for toes-up and toes-down surface tilts is quite different. During toes-up surface rotations, more than 75% of non-dancer head, trunk and pelvis variance was described by the first component while the second contributed another 15%. By contrast, the first component for dancers contributed 10% less to the overall variance (~65%) while the second component described close to ¼ of the total (25%). During toes-down surface rotations, the eigenvalues for the two groups were more similar (~80% and 15%).

The individual contributions of each of the nine kinematic variables to the overall variance for the first and second principal components is shown in Figure 5.3A (roll/diagonal plane perturbations) and in Figure 5.3C (pitch plane perturbations). The mean time courses, or expansion coefficients, of the components are shown in Figure

5.3B and D. During roll/diagonal surface tilts (Figure 5.3A and B), the first principal component was stronger (i.e. larger magnitude) for dancers than non-dancers. In addition, dancers demonstrated less group variability particularly during correction phase II and the stabilizing phase at which time the second principal component was engaged. Particularly striking when the individual variables are considered was the larger contribution of the pelvis in the frontal and horizontal planes as well as the trunk in the horizontal plane in the first component for dancers. The dancers' second component was primarily comprised of sagittal and frontal plane trunk and three-dimensional head displacement. However, for non-dancers, variable contributions to the second component were more evenly distributed. Also important to note is the increased contribution of frontal plane trunk displacement in non-dancers to the first component during pure roll plane perturbations. Dancers were more discriminating in their initial use of the trunk in that, for the sagittal and frontal planes, the percent variance captured by the first component was much less than in the horizontal plane, for all directions. This difference was not observed as strongly for non-dancers. It appears that during roll and diagonal tilts, dancers were able to make an orientation change and then maintain the new position. During toes-up surface tilts, behavior of the first principal component was similar for the two groups (Figure 5.3C and D). Differences in variable contributions included an increase in horizontal pelvis and frontal and sagittal head displacement for non-dancers. As for the second component, dancer response was larger, as was mentioned above, while each of the nine variables contributed to the response. When data from toes-down perturbations are considered (Figures 5.3C and D), immediately striking was the large contributions of frontal plane pelvis displacement and sagittal plane head displacement for the second component in the dancer response. The magnitude of the first component was larger for dancers with more of the total variance due to sagittal pelvis displacement as opposed to sagittal trunk displacement for non-dancers.

5.4.3 Intermediary joints

Knee and elbow flexion were present during surface tilting regardless of perturbation direction, however, there were no significant differences in flexion magnitude between the groups.

5.4.4 EMG responses

No statistically significant differences were found between the two groups with regards to muscle activation latencies. Activation of the shank muscles, approximately 100 ms after platform onset, preceded activation of the other muscle groups tested. A more complete description of the activation patterns have been described elsewhere (Hughey and Fung submitted 2003).

Figure 5.4A shows the raw EMG trace from a representative dancer and non-dancer during a right diagonal toes-up tilt. The integrated EMG muscle activation patterns during correction phase I (70 – 195 ms), correction phase II (195 – 320) and the stabilizing phase (320 – 670 ms) are illustrated in Figure 5.4B. For the ankle muscles (TA and MG), group differences in response magnitudes were found for TA during correction phase I ($F_{[1,18]} = 4.60$; $P<0.02$) and MG during the stabilizing phase ($F_{[1,18]} = 7.08$; $P<0.05$). TA activation was greater in dancers particularly during toes-up and right diag toes up rotations (i.e. when the limb is unloaded) as was confirmed by pairwise comparison ($F_{[7,126]}$ = 6.02; P<0.0001). On the other hand, MG response during the stabilizing phase was larger for non-dancers regardless of the perturbation direction. Overall knee muscle activation during surface tilting was small as compared to voluntary leg lifting (see Hughey and Fung submitted 2003). However, non-dancer RF activation was always greater regardless of the time period analyzed (correction phase I – $F_{[1,18]}$ = 22.55; P<0.0005; correction phase II – $F_{[1,18]}$ = 5.69; P<0.05; stabilizing phase – $F_{[1,18]}$ = 13.22; P<0.002). A group vs tilt direction interaction was found during correction phase I ($F_{[7,126]}$ = 2.15; P<0.05) where the only direction that was non-significant was for left diag toes-up perturbations. A main group effect as well as a group vs tilt direction interaction for ST activation was found only during the stabilizing phase ($F_{[1,18]}$ = 10.95; P<0.005; $F_{[7,126]}$ = 2.18; P<0.05). Further pairwise comparisons revealed a greater non-dancer response following toes-up, toes-down and diag toes-down surface tilts. As for the hip muscles, AD and TFL, a significant main group effect was found only for the TFL during the stabilizing phase ($F_{[1,18]}$ = 16.60; P<0.001). Again, non-dancer response was larger regardless of perturbation direction. The magnitude of trunk muscle activation was greater in non-dancers in all analysis periods with the exception of ES during correction phase II (RA: correction phase I – $F_{[1,18]}$ = 20.18; P<0.0005; correction phase II – $F_{[1,18]}$ = 16.90; P<0.001; stabilizing phase – $F_{[1,18]}$ = 34.61; P<0.0001; ES: correction phase I – $F_{[1,18]}$ = 4.97; P<0.05; stabilizing phase – $F_{[1,18]}$ = 6.57; P<0.02). Throughout the stabilizing phase, dancers relied mostly on activation of the shank muscles with AD and ES contributing following right side-up surface tilts. However, the magnitude of non-dancer muscle response was more evenly dispersed for the muscles instrumented.

One striking difference between dancers and non-dancers was found with respect to the magnitude of muscle activity during the 70 ms following perturbation onset (reflex phase). Non-dancer muscle activation was significantly greater for all eight muscles regardless of tilt direction (TA – $F_{[1,18]} = 24.18$; $P<0.0001$; MG – $F_{[1,18]} = 22.32$; $P<0.0005$; RF – $F_{[1,18]} = 31.62$; $P<0.0001$; ST – $F_{[1,18]} = 26.90$; $P<0.0001$; AD – $F_{[1,18]} = 14.65$; $P<0.005$; TFL – $F_{[1,18]} = 32.61$; $P<0.0001$; RA – $F_{[1,18]} = 69.03$; $P<0.0001$; ES – $F_{[1,18]} = 36.92$; $P<0.0001$).

5.5 Discussion

The aim of the present study was to characterize the postural response strategies used by dancers as compared to non-dancers following an unexpected perturbation to stance. A moderate degree of multi-directional surface tilting was chosen. Since the task requires a weight shift from double to single limb support for most perturbation directions (see Figure 5.1B), these results can be compared with our previous study of multi-directional voluntary leg lifting (Hughey et al. submitted 2003). Overall, our results indicate that all subjects succeeded at the task (i.e. did not step or fall), with only subtle differences in recovery strategy demonstrated by the two groups. Statistically significant differences between dancers and non-dancers were found in the horizontal COP excursion and the amplitude of muscle activity. Also, principal component analysis revealed differences in segmental coordination patterns between the groups which were dependent upon the perturbation direction.

5.5.1 Stereotypical responses to unexpected perturbation

Automatic postural responses following an unexpected loss of balance are triggered by sensory input resulting from the perturbation. They consist of fast bursts of muscle activity that act to restore postural stability. In addition, these responses have been shown to follow a fixed pattern which is independent of predictability and experience. For example, the automatic postural responses evoked by horizontal surface translations in cats involved a "force constraint" strategy which was not altered by knowledge of the upcoming perturbation direction or familiarity with the task

(Macpherson 1994). However, the scaling of the response has been found to be influenced by experience (Horak et al. 1989). Also, Inglis et al. (1994) have shown that the triggering mechanism which generates an automatic postural response can affect both its timing and scaling.

With regards to the current study, as we hypothesized, a common control strategy was utilized by both dancers and non-dancers. In general, muscle activation followed a distal-to-proximal pattern for all perturbation directions (for a complete description see Hughey and Fung submitted 2003). Response scaling was where differences between the groups were found. Dancer control relied heavily on activation of the ankle muscles, particularly TA throughout the entire trial as is shown by the large IEMG areas in the first two columns of Figure 5.4. Non-dancers used more knee, hip and trunk musculature (Figure 5.4 columns 2, 3 and 4). These results are consistent with our belief that through training, dancers maintain balance and posture primarily through proprioceptive feedback. Contraction of the ankle muscles was used to create the necessary adjustments to control COM displacement through COP manipulation. Non-dancers, on the other hand, attempted to stabilize the trunk by a general stiffening of all the muscles tested. In particular, non-dancers relied on contraction of RF and RA. Regardless of perturbation direction, non-dancer activation of these muscles was always greater than for dancers. Consider first RF. In most cases, surface tilting resulted in non-dancer flexion of both the loaded and unloaded knee. Dancers also demonstrated a similar degree of knee flexion, although these results are misleading. Nine out of the eleven dancers who participated in this study were hyper-extended at the knee joint. So, the knee flexion observed was due to a return to a neutral position. Non-dancers, on the other hand, used flexion of the knee as part of their postural control strategy to lower the COM as is illustrated by the increased RF activation. As for RA, it was maximally activated during correction phase I following toes-down rotations for both groups. However, the magnitude of RA activity which the non-dancers demonstrated was nearly twice that of dancers. By the stabilizing phase, that discrepancy increased significantly. In fact, during the stabilizing phase, non-dancer activation magnitudes for all muscles tested, with the exception of TA and AD, were larger. Clearly, non-dancers required more energy to recover balance and equilibrium than dancers.

5.5.2 Automatic response triggering sources following unexpected perturbation

Both ankle and trunk afferents have been suggested as possible triggering sources for automatic postural responses (Allum and Honegger 1998; Carpenter et al. 1999; Henry et al. 1998b; Inglis et al. 1994). Evidence in support of either mechanism has been presented based on muscle onset latencies and corresponding kinematic adjustments. For example, Inglis et al. (1994) presented horizontal surface translations at various velocities and amplitudes to patients with somatosensory loss due to diabetic neuropathy and matched controls. Both groups demonstrated a distal-to-proximal muscle activation pattern, but the patient response was delayed and did not scale according to changes in perturbation characteristics. Therefore, it was concluded that somatosensory information from the lower legs is critical for triggering responses but that redundancy in the sensory system still allows the generation of specific response patterns. On the other hand, following multi-directional surface rotation, Carpenter et al. (1999) reported early stretch/release of the paraspinal muscles (40-60 ms) that was coincident with angular trunk velocity following roll plane and combined roll/pitch perturbations. These results led the researchers to conclude that proprioceptive signals from the trunk are responsible for triggering fast balance corrections. However, it should be noted that, unlike the present study, participants were strapped to the support surface which may have led to altercations in the activation patterns of the more distal muscles. We observed early activation of the trunk muscles only in the toes-down and toes-down diagonal directions (Hughey and Fung submitted 2003). Since our subjects were required to stand in an externally rotated foot position, the shape of the support base affords more medial/lateral than anterior/posterior stability (refer to Figure 5.1). Therefore, pitch plane perturbations are more destabilizing and require a faster, stronger response to avoid a fall.

It appears that both mechanisms may be used to trigger automatic responses. Our results are consistent with the sensory integration model described by Mergner and colleagues (Mergner and Rosemeier 1998). The proposed model involves central control of posture through the upward channeling of proprioceptive information from foot contact with the support surface as well as the down channeling of visual and vestibular information from the head. Through the synthesis and weighting of this information the central nervous system is provided with an accurate internal model of the position and movement of the body in space as well as information concerning the support surface. The weighting of the individual inputs is driven by environmental factors. Control is dominated by proprioceptive information when the support surface is firm and stable whereas if the support surface is unstable (i.e. small or compliant) then visual and vestibular input gain importance. In our case, since the support surface went through a period of instability as it was rotated, we would expect normal response to include active stabilization of the head and trunk in space so as to improve the quality of feedback information received from the visual and vestibular systems. Indeed, our data for non-dancers support this theory. Non-dancers minimized head and trunk displacement with greater activation of the trunk muscles than dancers. On the other hand, dancers appear to have developed a greater weighting for proprioceptive afferents as was demonstrated by larger COP excursion and pelvis stabilization.

Balance was recovered by both groups partially through manipulation of the COP as is shown in Figure 5.1C. COP shifting always preceded as well as exceeded COM displacement. Evidence of the control of COM through COP positioning has been found in activities ranging from quiet stance to leg lifting to trunk bending in microgravity (Hughey and Fung submitted 2003; Massion et al. 1997; Winter et al. 1996). In our previous study we showed that during voluntary leg lifting both dancers and non-dancers used COP adjustment for balance control but, for dancers the oscillations were of lower magnitude and higher frequency (Hughey et al. submitted 2003). We agree with Hugel et al. (1999) that these small fast COP shifts provided important proprioceptive information concerning the foot-surface interface which enabled dancers to be more precise in their control.

In response to surface tilting, we did not find a similar discrepancy in shift frequency during the first 700 ms. It is interesting to note that, although not presented here, we did find that dancers increased the frequency of their COP adjustments after the 700 ms time window whereas non-dancers demonstrated more head and trunk movement. During the initial response time, however, both dancers and non-dancers controlled COM displacement by manipulating the COP against the perturbation. Thus, the specific use of

COP shifting in response to surface tilting appears to be a common response strategy for both dancers and non-dancers.

One significant difference we did find between the two groups was that dancers used a larger total COP excursion which was more variable than non-dancers regardless of perturbation direction (Figure 5.2). We believe this to be indicative of the dominance of proprioceptive feedback in the dancer response. Ballet dancers have been trained to maintain an upright vertical posture while executing complicated, multi-segmental movements. With the head and trunk stabilized, proprioceptive input becomes essential for balance control. If, as we hypothesized, dancers rely more heavily on a proprioceptive triggering mechanism to control posture and recover balance then performance should be compromised in situations where COP control is challenged. Indeed, following pure pitch plane perturbations (toes-up and toes-down), in which the contribution of COP to the control of COM positioning is reduced due to the rotated stance position, dancers had more difficulty maintaining balance as was illustrated by the principal component analysis of the kinematic variables.

5.5.3 Influence of perturbation direction on segmental coordination

Previously, we have shown that dancers actively control vertical head and trunk orientation during fast leg lifting (Hughey et al. submitted 2003). The weight shift to single limb support is achieved smoothly through pelvis rotation. Non-dancers minimize COM displacement through inclination of the trunk away from the lifting leg. These results were consistent for all lift directions. In the current study, we found no differences in the magnitude of head, trunk and pelvis displacement, but principal component analysis did uncover interesting variations in segmental coordination. Kinematic responses in both groups were dependent upon perturbation direction. During surface tilts which involved a mediolateral weight transfer (side and diagonal tilts), dancers responded more efficiently than non-dancers whereas during pitch plane surface tilts (toes-up and toes-down), dancer control was more complex.

First, consider the pattern of kinematic control associated with roll plane (side unload) and diagonal surface tilts. As was clearly demonstrated by the slope and magnitude of the first expansion coefficient, the initial dancer response was stronger than the non-dancer response (Figure 5.3). The fact that the first principal component found for dancers was dominated by pelvis and horizontal trunk displacement is expected, based on our previous results; during multi-directional leg lifting we also found that dancers employed a control strategy which focused on the feedforward adjustment of the pelvis to maintain vertical trunk alignment (Hughey et al. submitted 2003). Non-dancers, on the other hand, used trunk displacement as a means by which COM control was facilitated. Here again, during surface tilting, in addition to the expected frontal plane rotation of the pelvis, initial non-dancer response involved a larger contribution of the trunk as compared to dancers. The second principal component was more evenly distributed among the nine variables for non-dancers, while dancers made secondary adjustments predominately in head and trunk positioning. All of these data combined together lead us to suggest that dancers responded to roll and diagonal surface tilts in a more feedforward manner than non-dancers. After the first adjustment, dancers stabilized the pelvis to provide an interface between the support surface and the vertical gravity axis. Further control of the COM was achieved through sensory feedback.

Pitch plane surface rotation results differed. Toes-up rotations resulted in a horizontal twisting of the pelvis in non-dancers which was noticeably smaller in dancers. We believe that this represents an attempt by non-dancers to control A/P displacement by shifting more weight onto one foot. Inaguri (1983) has suggested that the right and left foot each play a different role in the maintenance of posture, one provides support while the other controls posture. Dancers, on the other hand, are very task driven and strove to maintain even weight distribution across the feet even if performance was affected. During multi-directional leg lifting, non-dancers demonstrated a preference for left limb support that dancers did not. Here again, during multi-directional surface tilting, non-dancers were better able to minimize M/L COM displacement following right side-up tilts as opposed to left side-up tilts (Figure 5.2B). It might seem that flexibility of the ankle joint may come into question, but Khan et al. (1997) have shown that there is no significant difference in the range of passive dorsiflexion between ballet dancers and control subjects. Rather, any performance limitations are due to anatomical constraints and should be evident in both groups.

Interestingly, sagittal head displacement contributed more to the overall variance described by the first principal component in dancers while frontal and horizontal plane head displacement was more prominent in non-dancers. These results suggest that the dancers were better able to lock the head to the trunk and thus simplify the control process by reducing the number of joints to be controlled. Toes-down surface tilts provided dancers the most difficulty. Although not readily apparent, the dancers involved in this study were all hyper-extended at the knee joint and tended to stand with their knees in a "locked position". Since the stance position was externally rotated, during roll plane and diagonal surface tilts, the unloaded knee naturally unlocked whereas during toes-down tilts, the resultant knee flexion caused a forward displacement of the COP which then had to be controlled. Also significant is the magnitude of frontal plane pelvis displacement present in the second principal component for dancers (~50%). Again this may be the result of a preference of one limb for stance control. Hugel et al. (1999) have shown dancers to possess a dominant limb during quasi-static balance whereas our examination of dancers during multi-directional leg lifting yielded no such finding (Hughey et al. submitted 2003).

5.5.4 Conclusions

In conclusion, the present study has emphasized the role of dance training on postural control and coordination. Expertise in dance was not found to influence the postural control strategy employed to regain balance and equilibrium. However, subtle differences between the two groups were discovered. We suggest that skill in classical ballet leads to a shift in sensory input dominance from vision to proprioception. Therefore, the pertinence of a dance training program for patient populations in which the visual or vestibular systems have been compromised is implicated. Further research should include the elimination of visual input during the task as well as subjects representing different age groups.

5.6 References

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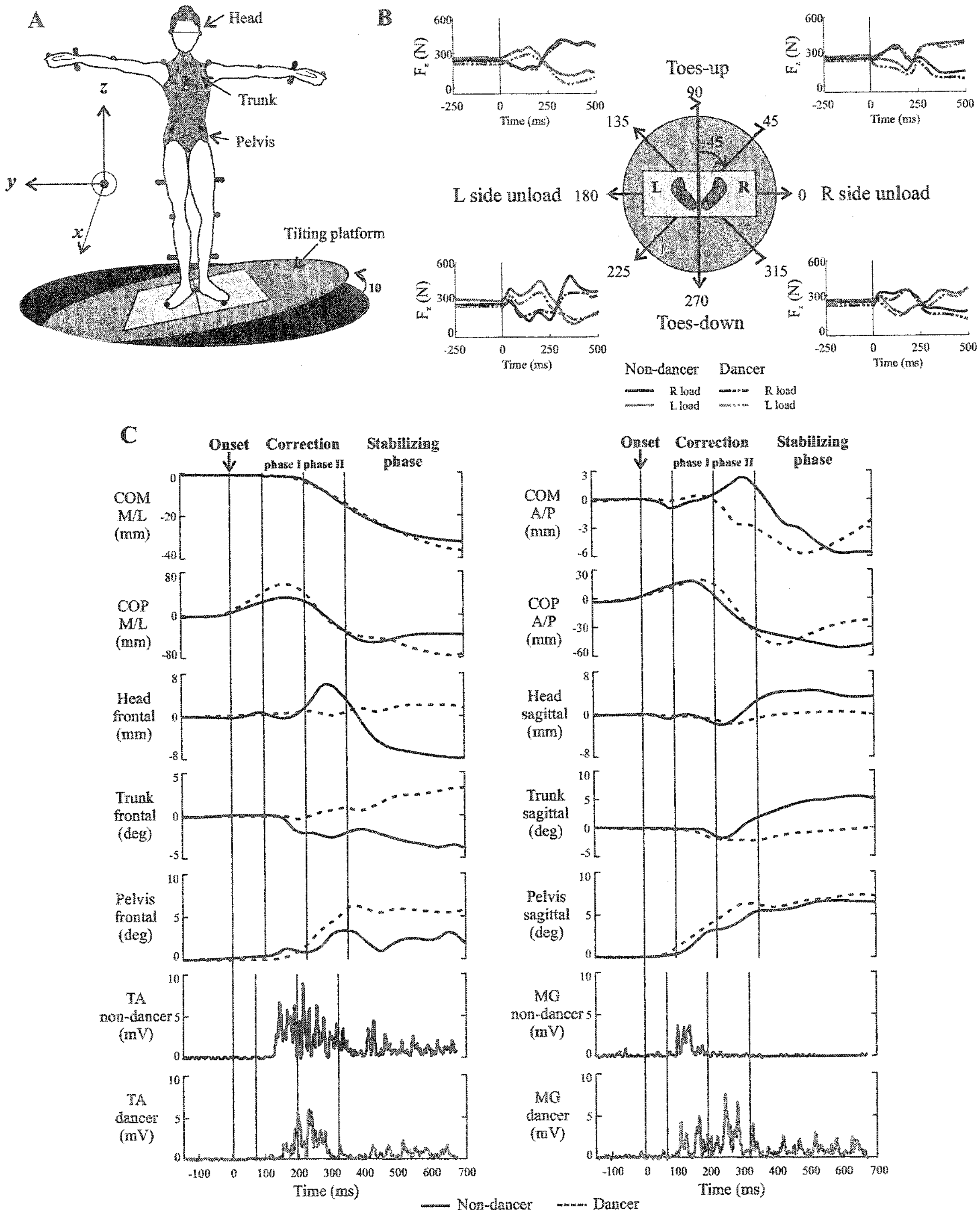
5.7 Tables & Figures

Table 5.1 Eigenvalues and percent variance captured by the first two principal components for changes in three-dimensional head, trunk and pelvis orientation.

	Non-dancers				Dancers			
	PCA #	Eigenvalue of Cov(X)	% Variance Captured this PC	% Variance Captured Total	PCA #	Eigenvalue of Cov(X)	% Variance Captured this PC	% Variance Captured Total
R side-up	1	11.29	81.57	81.57	1	20.11	96.37	96.37
(0°)	2	1.92	13.86	95.42	2	0.42	2.03	98.4
R diag toes-up	1	7.49	83.77	83.77	1	13.75	95.74	95.74
(45°)	2	1.16	12.96	96.73	2	0.35	2.47	98.20
Toes-up	1	1.46	76.08	76.08	1	0.86	65.87	65.87
(90°)	2	0.31	16.21	92.29	2	0.32	24.60	90.48
L diag toes-up	1	6.30	84.22	84.22	1	10.33	94.08	94.08
(135°)	2	0.91	12.14	96.36	2	0.34	3.13	97.21
L side-up	1	12.07	85.48	85.48	1	17.3	95.36	95.36
(180°)	2	1.50	10.59	96.07	2	0.54	2.98	98.34
L diag toes-down	1	7.18	79.87	79.87	1	8.76	88.53	88.53
(225°)	2	1.28	14.25	94.13	2	0.90	9.06	97.59
Toes-down	1	2.60	80.83	80.83	1	1.92	78.16	78.16
(270°)	2	0.45	14.00	94.83	2	0.44	17.88	96.04
R diag toes-down	1	7.53	79.48	79.48	1	11.02	92.93	92.93
(315°)	2	1.36	14.32	93.80	2	0.64	5.37	98.30

Figure 5.1 A) Kinematic set-up with 34 markers. Small circles show reflective marker placement (white circles represent posterior trunk and pelvis markers). The kinematic coordinate system (*x*-*y*-*z*) is shown on the side. Surface is tilted to a height of 10° at a rate of 53°/s. B) Coordinate system for unexpected surface tilts. Arrow indicates surface tilt direction. Insets show loading and unloading forces from a representative dancer and non-dancer (black lines – right force plate; gray lines – left force plate). Solid lines are data from the non-dancer and dashed lines correspond to data from the dancer. C) COM and COP displacement, head, trunk and pelvis rotation and shank muscle activation during a right diagonal toes-up surface tilt (45°) for a representative non-dancer (solid line) and dancer (dashed line). Column 1 shows frontal plane and TA data and column 2 shows sagittal plane and MG data. Note: kinematic integrals are offset from EMG by 30 ms.



A
Head
Trunk
Pelvis
z
y
x
Tilting platform
10
B
Toes-up
90
135
45
L side unload
180
0
R side unload
225
315
270
Toes-down
L
R
F_z (N)
Time (ms)
Non-dancer
Dancer
R load
L load
C
Onset
Correction
phase I phase II
Stabilizing phase
COM M/L (mm)
COP M/L (mm)
Head frontal (mm)
Trunk frontal (deg)
Pelvis frontal (deg)
TA non-dancer (mV)
TA dancer (mV)
COM A/P (mm)
COP A/P (mm)
Head sagittal (mm)
Trunk sagittal (deg)
Pelvis sagittal (deg)
MG non-dancer (mV)
MG dancer (mV)
Time (ms)
Non-dancer
Dancer

Figure 5.2 COM/COP. A) Total peak-to-peak displacements of the COM and COP for all surface tilt directions. Black triangles signify the dancer group (+SE) and gray triangles signify the non-dancer group (+SE). Scale magnitude for COM displacement is ½ that of COP. B) Total distance traveled by the COM (*x-y-z*) and COP (*x-y*) from 0 700 ms following perturbation onset. Data are an average of all trials from all subjects. Dancers are shown as black triangles (±SE) and non-dancers are white circles (±SE).

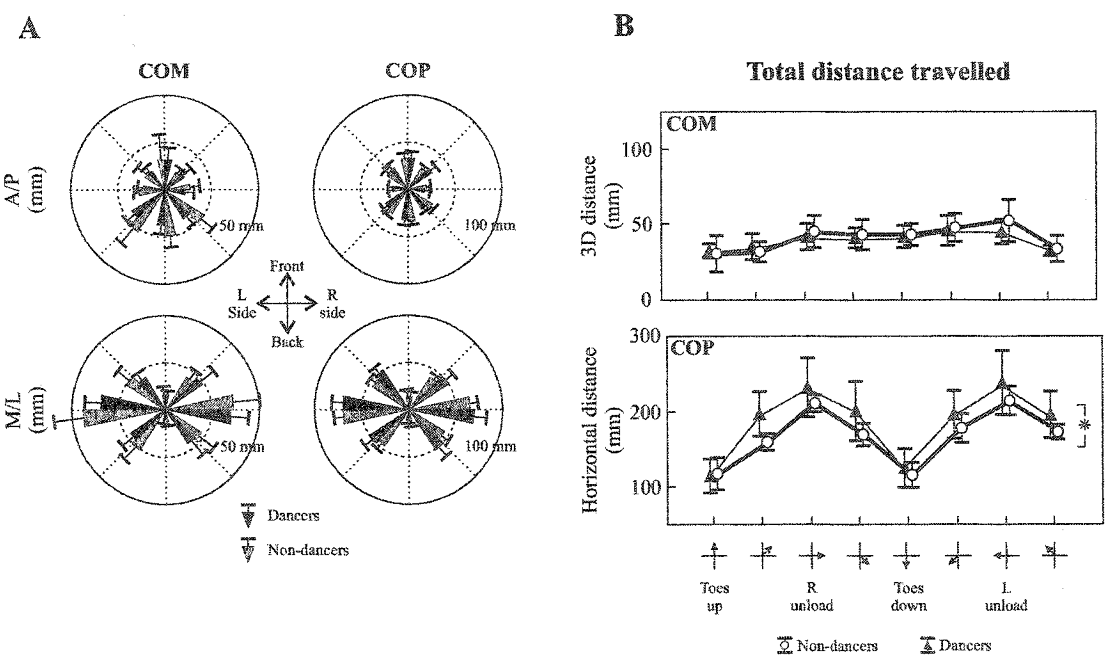

A
COM
COP
A/P (mm)
M/L (mm)
50 mm
100 mm
Front
Back
L Side
R side
Dancers
Non-dancers
B
Total distance travelled
COM
3D distance (mm)
0
50
100
COP
Horizontal distance (mm)
100
200
300
*
Toes up
R unload
Toes down
L unload
Non-dancers
Dancers

Figure 5.3 PCA for head, trunk and pelvis. A & C) Percentage of the 3-dimensional head, trunk and pelvis angle data which are described by the first two principal components for dancers (right) and non-dancers (left) during roll plane and diagonal tilts (A) and pitch plane tilts (C). B & D) Scaled time course (± SE) of the first two principal components (1^{st} – top graph, 2^{nd} – bottom graph). Variability in the dancer group (dashed line with gray area) versus variability in the non-dancer group (solid line with hatched area) during roll plane and diagonal tilts (B) and pitch plane tilts (D).

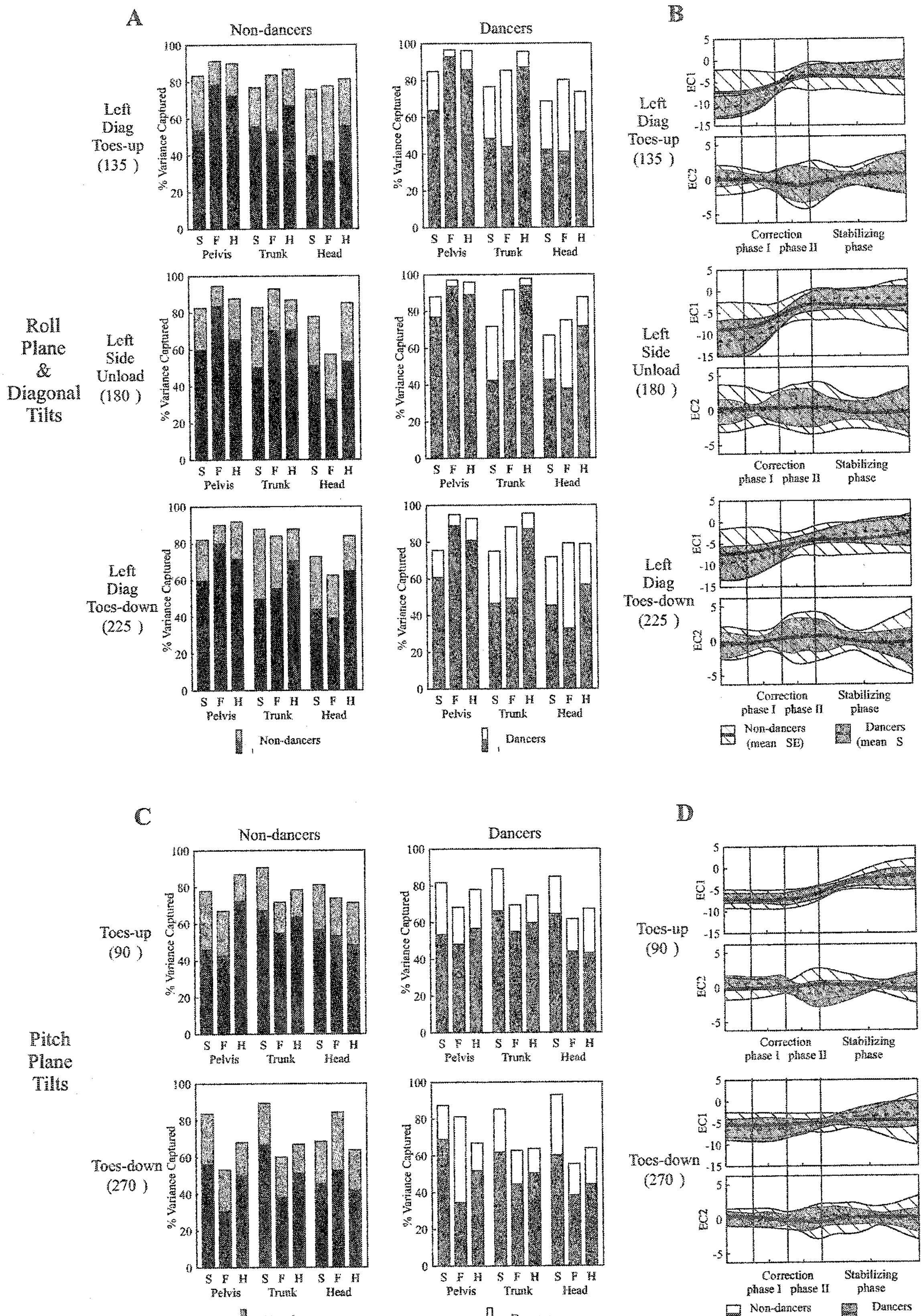
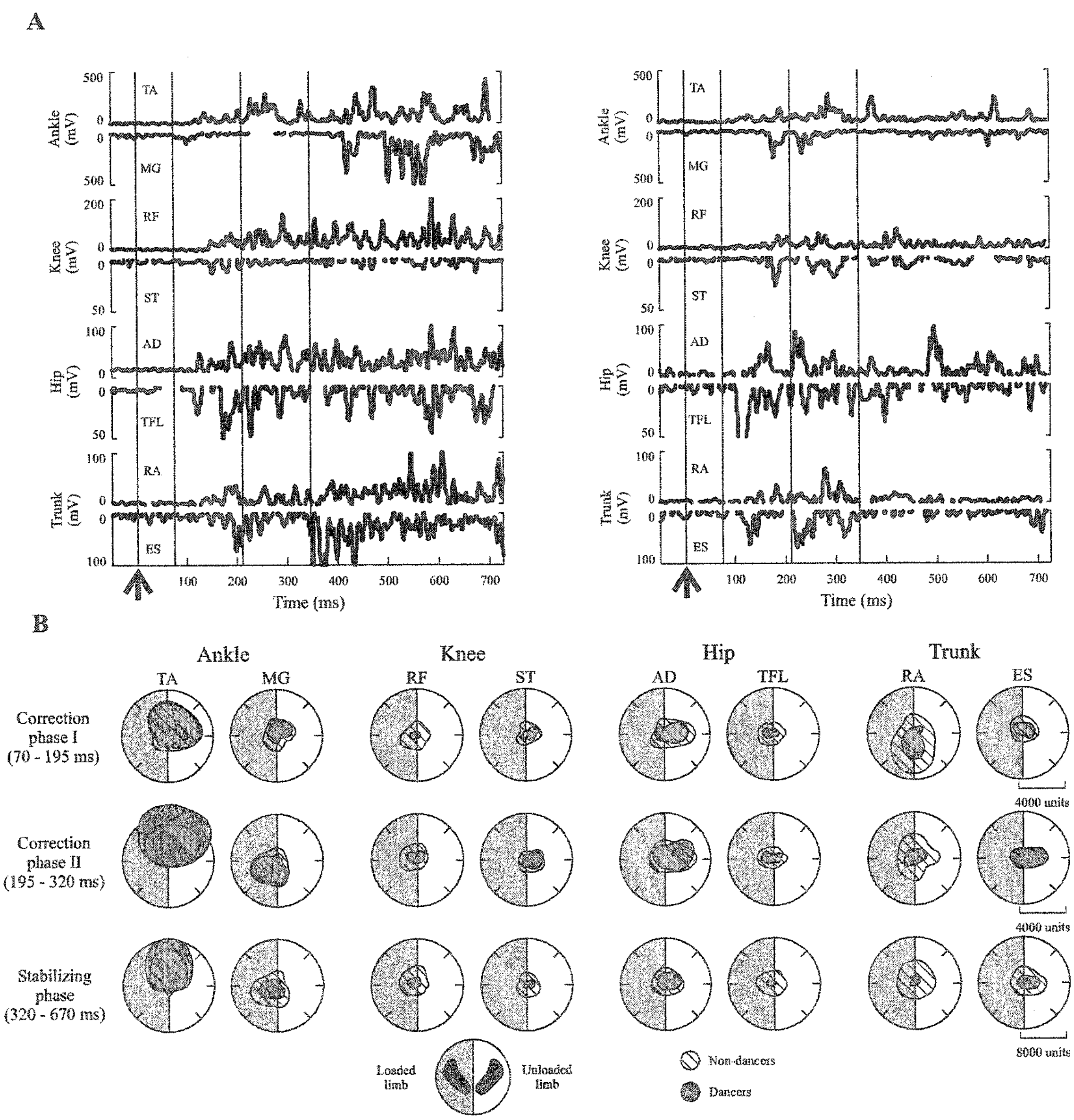

A
Non-dancers
Dancers
B
Roll
Plane
&
Diagonal
Tilts
Left
Diag
Toes-up
(135)
Left
Side
Unload
(180)
Left
Diag
Toes-down
(225)
% Variance Captured
S F H S F H S F H
Pelvis Trunk Head
EC1
EC2
Correction
phase I phase II
Stabilizing
phase
Non-dancers
Dancers
Non-dancers
(mean SE)
Dancers
(mean S
C
Non-dancers
Dancers
D
Pitch
Plane
Tilts
Toes-up
(90)
Toes-down
(270)
% Variance Captured
S F H S F H S F H
Pelvis Trunk Head
EC1
EC2
Correction
phase I phase II
Stabilizing
phase
Non-dancers
Dancers
Non-dancers
(mean SE)
Dancers
(mean S

Figure 5.4 EMG. A) Sample EMG data from a representative dancer and non-dancer for four muscle pairs during a right diagonal toes-up surface tilt. B) Muscle tuning curves for four right muscle pairs (ankle – TA, MG; knee – RF, ST; hip – AD, TFL; and trunk – RA,ES). Shaded semi-circle indicates activity when the leg is in stance (during left leg lifts) and white semi-circle indicates activity when the leg is in swing (during right leg lifts). Dancers are gray shaded areas and non-dancers are shown by hatched areas.


A
Ankle (mV)
TA
MG
Knee (mV)
RF
ST
Hip (mV)
AD
TFL
Trunk (mV)
RA
ES
Time (ms)
B
Ankle
Knee
Hip
Trunk
Correction phase I (70 - 195 ms)
Correction phase II (195 - 320 ms)
Stabilizing phase (320 - 670 ms)
4000 units
4000 units
8000 units
Loaded limb
Unloaded limb
Non-dancers
Dancers

Chapter 6 Conclusions

This thesis explored the adaptability of the central nervous system in the control of upright vertical posture. Several novel protocols were used to determine these effects. First, a comparison was made between the response strategies generated by voluntary leg lifting versus externally triggered surface tilting. Both tasks involved a weight shift from double to single limb support and were performed in multiple directions. To date, no other study has examined the different control methods used to maintain balance during multi-directional voluntary and externally triggered weight transfers. Three-dimensional kinematic responses were measured. Most research in this area has been limited to single plane recordings from perturbations evoked by voluntary actions or surface manipulations in the same plane. However, this thesis presents multi-dimensional data from multi-directional perturbations. Through this protocol, anticipatory and reactive control strategies could be compared and contrasted. Next, the effect of classical ballet training on postural response during leg lifting and surface tilting was examined. Ballet dancers were age, height and weight matched with athletic non-dancers. Recreational athletes were chosen as controls to reduce the possibility that any group differences were due to strength rather than the specific training regime. Kinematic strategies were determined by principal component analysis (PCA) performed on three-dimensional data sets. The results presented here are the first to describe a complete pattern of three-dimensional kinematic response where in previous works PCA has been used to analyze responses for each movement axis independently.

6.1 Summary of results

This thesis has shown how the postural control system modifies response strategies to adjust for task demands and experience gained through specific athletic training. The following conclusions can be drawn:

1. **Control system redundancy is reduced through the recruitment of specific postural strategies that are selected based on the task goal.**

The main postural goal during weight shifting is control of COM displacement, whether movement is triggered externally or internally. If the mandatory shift in COM position is not controlled, a fall will occur. Many similarities were found in the postural responses during the two tasks. In order to achieve COM control, two variables were actively adjusted: segmental orientation and COP. Assuming that postural equilibrium takes priority over orientation, the interface of the feet with the support surface becomes a significant source of balance control. Analysis of the temporal relationship between COM and COP during voluntary leg lifting demonstrated the use of advanced changes in COP position to control COM displacement. Also, once a target position was reached (voluntary) or a posture was to be maintained (unexpected), the COM was encompassed by an oscillating COP. Reduction of joint segment redundancy, which simplifies the control process, was illustrated by head, trunk and pelvis coordination. Unexpected surface tilting elicited an automatic response strategy which focused on control of trunk orientation with respect to the vertical gravity vector. Since the trunk represents a major contributor to the total body COM, stabilization of the trunk reduces COM displacement.

During fast leg lifting, vertical trunk orientation was compromised for movement generation and the recovery of postural equilibrium. In this case, displacement of the trunk is used to counteract the effects of the leg extension. Throughout both tasks the integrity of the visual input was maintained by the stabilization of the head in space. Therefore, the requirements of the task and not the task itself appear to govern the selection of postural control strategy. These results have implications for the analysis and rehabilitation of patient populations. For tasks which involve a change in the support configuration, control of balance and not movement performance should take precedence in treatment strategy.

2. **Classical ballet dancers demonstrate improved balance performance during multi-directional leg lifting.**

Classical ballet dancers and athletic non-dancers used different control strategies to both execute a leg lift and maintain the final single limb posture. The most significant differences between the groups were found in terms of kinematic strategy. Trained dancers maintained vertical head and trunk orientation independent from lift direction while non-dancers compromised vertical trunk alignment. Principal component analysis revealed that dancers primarily used an early three-dimensional pelvis adjustment to minimize COM displacement which was more efficient and less disrupting. Non-dancers had more difficulty controlling ballistic leg lifts as was illustrated by the magnitude of the second principal component as well as the inter-subject variability. The trunk stabilization in space demonstrated by dancers proved to be a better control strategy as was shown by the tuning and amplitude of muscle activation patterns, particularly in the more proximal postural muscles. Non-dancer displacement of the trunk for movement generation and COM stabilization required larger, less focused bursts of activity. Energy output during leg lifting was minimized through dance training. It can be concluded that ballet dancers have learned to perform multi-directional leg lifts in a well-defined, cost effective way. These results stress the importance of vertical trunk alignment during weight shifting tasks. Therefore, training regimes such as ballet dancing which promote trunk stabilization may be useful for improving balance skills in voluntary tasks which involve displacement of the lower limbs.

3. Multi-directional surface tilting produces stereotyped postural responses which are subtly modified in classical ballet dancers.

For the most part, no differences were found between ballet dancers and athletic non-dancers in response to multi-directional surface tilting. Head, trunk and pelvis displacements as well as COM excursion were the same for both groups. In addition, muscle activation latencies and the temporal characteristics of COM and COP displacement were similar. However, total horizontal distance traveled by the COP was larger and more variable for dancers than non-dancers. PCA performed on the kinematic variables revealed that dancers used a more complex response pattern which was dependant upon surface tilt direction. Also, the activation patterns of the knee, hip and trunk muscles exhibited by dancers were more finely tuned to the direction of the perturbation. These results suggest that triggered postural responses are preprogrammed and not learned responses. The balance skills demonstrated by classically trained dancers during leg lifting are not transferable to surface tilting. However there was some evidence that training in classical ballet leads to modifications in the control process. Therefore the implementation of some sort of dance training program for populations in which the visual of vestibular systems have been compromised may be implicated.

6.2 Implications for future studies

The results described in this thesis provide valuable information concerning the adaptability of the central nervous system in the control of upright posture. With this new knowledge comes insight into how training programs can be geared to improve balance skills. However, before the benefits of dance training on everyday balance capabilities can be expounded, further research needs to be conducted. First, the model with which postural control was assessed for this thesis should be expanded to include arm movement at the shoulder joint, angular changes at the ankle joint as well as the calculation of joint torques and COM/COP velocities and accelerations. These additional analyses may uncover significant differences between dancer and non-dancer response strategies, especially following unexpected surface tilting. Next, these experiments should be performed with subjects representing different age groups and levels of training. For instance, it would be interesting to compare the postural responses of 50+ year old retired dancers with age matched controls. Do these subjects use different postural strategies? Also, do retired dancers use different control strategies than active dancers? With respect to training, a question will always arise concerning the predilection of certain individuals to study classical ballet. Body type plays a significant role in the selection of potential dancers. Therefore, studies which include a wider range of dancers, not just high-level dancers, will increase our understanding of the specific effects of classical ballet training on balance skills. Finally, this research should be expanded to include sensory deprivation or conflict. In previous studies, it has been suggested that athletic training in sports which involve balance control leads to a shift in sensory dominance from the visual to the proprioceptive system (refer to section 2.4). If this was found to be true for individuals with dance training, the implementation of dance as a preventative tool for treating the aging population may be indicated since visual acuity decreases with age.

Appendix