The control of whole-body equilibrium and trunk stability during sudden hand loading.

Monica Lynn. Haumann

University of Windsor

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THE CONTROL OF WHOLE-BODY EQUILIBRIUM AND TRUNK STABILITY
DURING SUDDEN HAND LOADING

by

Monica L. Haumann

A Thesis
Submitted to the Faculty of Graduate Studies and Research
through Human Kinetics
The University of Windsor
in Partial Fulfillment of the Requirements for the
Degree of Masters of Human Kinetics at the
University of Windsor

Windsor, Ontario, Canada

2002
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Abstract

THE CONTROL OF WHOLE-BODY EQUILIBRIUM AND TRUNK STABILITY DURING SUDDEN HAND LOADING

Monica L. Haumann
University of Windsor, 2002

Advisor: Dr. James R. Potvin

Stability of the spine is an integral factor in determining the whole-body response to an induced perturbation, upon maintaining postural equilibrium. The purpose of this study was to examine whole-body and trunk postural control to sudden loading at the hands, with a special focus on the implications of loading to spinal stability. Seventeen females experienced the effects of load symmetry, both symmetrical and asymmetrical, in combination with expected and unexpected anticipation. The dependent variables were pre-averages, anticipatory, peak and time-to-peak responses from four trunk and three leg muscles bilaterally. Pre-activation of trunk and leg agonistic muscles served to reduce the overall postural disturbance caused by sudden loading. An increase in antagonistic co-activation was observed in both the anticipatory and reflex-mediated compensatory responses to the load perturbation. It is proposed that muscle stiffness and co-activation strategies affect both trunk and whole-body stability. The results provide insight into several common mechanisms involved in the dynamic stability of whole-body equilibrium and spinal stability.
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Lastly, a huge hug to my friends. Each of you in your own way has been a great support. Thank you for seeing me through to the end.
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<th>Full Form</th>
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<tr>
<td>ADL</td>
<td>activity of daily living</td>
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<tr>
<td>AP</td>
<td>anterior-posterior</td>
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<tr>
<td>APA</td>
<td>anticipatory postural adjustment</td>
</tr>
<tr>
<td>BF</td>
<td>biceps femoris</td>
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<tr>
<td>BoS</td>
<td>base of support</td>
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<tr>
<td>CNS</td>
<td>central nervous system</td>
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<tr>
<td>CoM</td>
<td>centre of mass</td>
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<tr>
<td>CoP</td>
<td>centre of pressure</td>
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<tr>
<td>ECG</td>
<td>electrocardiography</td>
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<td>EMG</td>
<td>electromyography</td>
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<tr>
<td>ExO</td>
<td>external oblique</td>
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<tr>
<td>FWR</td>
<td>full-wave rectified</td>
</tr>
<tr>
<td>GRF</td>
<td>ground reaction force</td>
</tr>
<tr>
<td>IAP</td>
<td>intra-abdominal pressure</td>
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<td>InO</td>
<td>internal oblique</td>
</tr>
<tr>
<td>LBP</td>
<td>low-back pain</td>
</tr>
<tr>
<td>LES</td>
<td>lumbar erector spinae</td>
</tr>
<tr>
<td>MVC</td>
<td>maximum voluntary contraction</td>
</tr>
<tr>
<td>ML</td>
<td>medial-lateral</td>
</tr>
<tr>
<td>RF</td>
<td>rectus femoris</td>
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<tr>
<td>Sol</td>
<td>soleus</td>
</tr>
<tr>
<td>TA</td>
<td>tibialis anterior</td>
</tr>
<tr>
<td>TES</td>
<td>thoracic erector spinae</td>
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Chapter 1

INTRODUCTION

Stability and control of whole-body equilibrium is imperative to the performance of all tasks and activities of daily living (ADLs). Postural control ensures that balance is maintained during the execution of any static or dynamic task. Humans typically execute tasks almost automatically without being aware that certain body segments, or the equilibrium of the whole body, are actually being controlled. In the instance of workplace tasks, a large portion of injuries are incurred as a result of a sudden slip, fall or mishap that implicates both internal and external stability and threatens the equilibrium of whole-body mechanics (Manning and Shannon, 1981). To counter these disturbances, the neuromuscular system evokes anticipatory adjustments and postural strategies that act to maintain or regain stability. The central nervous system (CNS) rapidly selects the functionally most appropriate combination of sensory feedback within a given context. This sensory component is in conjunction with muscle coordination, which determines the temporal sequencing and the distribution and recruitment of muscle activation among the leg and trunk muscles to generate supportive reactions (Nashner, 1982).

Postural control can be classified into two categories termed ‘predictive’ or ‘reactive’. Predictive, or feedforward, control anticipates a disturbance and compensates prior to its occurrence. Reactive control evokes responses that are generated as supportive reactions to a perturbation. The CNS appears to incorporate predictive
control, even in compensatory responses to external perturbations, as the perturbation becomes familiar (Maki and McIlroy, 1997).

Anticipatory control of motor output enables fast and fluent execution of movement. This also applies to tasks in which the performance of movement brings about a disturbance to balance that is not completely predictable. The definitive example of an important predictive balance control mechanism is the anticipatory postural adjustment (APA). APAs are changes that occur prior to the equilibrium disturbance that is caused by the focal movement itself (Massion, 1992). Focal movements are defined as voluntary, goal-directed or primary movements (Cordo and Nashner, 1982). An APA is a predictive mechanism of postural control, which acts to minimize the destabilizing effects of the forthcoming movements in order to maintain the body in a state of equilibrium (Bouisset, Richardson and Zattara, 2000).

Stability of the lumbar spine is also an important factor in determining the whole body’s response to induced perturbations when maintaining postural equilibrium. The trunk constitutes an integral part of the motor system and represents a large part of the total body mass. In addition, it is evident that the spinal column is inherently unstable (Panjabi, 1992a). An adequate neuromuscular control of trunk movements and posture is, therefore, a prerequisite for the maintenance of body equilibrium during various motor tasks.

Much of the current spine literature has focused on mechanical stability of the spine. Mechanical stability is necessary to perform the fundamental functions of the spine such as: dynamic movements between body parts, carrying of external loads and protection of the spinal neural system (Panjabi, 1992a). Trunk muscle activity is needed
to maintain posture and bring about movement (Lavender, Tsuag, Andersson, Hafezi and Shin, 1992b). Aside from these functions, increased muscle activity also increases spinal stability through primarily two mechanisms: muscle stiffness and compressive forces. Both of these factors have been demonstrated to increase spine stability (Bergmark, 1989; Crisco and Panjabi, 1991; Janevic, Ashton-Miller and Schultz, 1991; Cholewicki and McGill, 1996).

Upon a perturbation being imposed to the whole-body equilibrium state, the neuromuscular response is designed to minimize the destabilizing postural disturbance and mechanical loading on the spine (Lavender, Marras and Miller, 1993). Epidemiological research identifies that a sudden, unexpected load on the lumbar spine is related to a high incidence of low-back injuries (Magora, 1973; Manning, Mitchell and Blanchfield, 1984). A sudden response of the neuromuscular control system supporting the spine greatly increases the mechanical loading on the spine (Marras and Mirka, 1989; Lavender et al., 1993; Cresswell, Oddsson, Thorstensson, 1994; Thomas, Lavender, Corcos and Andersson, 1998). The dynamic component of sudden loading is derived from the external application of a force, such as a load being applied to the hands. This requires that additional muscle force be generated to minimize the disturbance to the body’s posture. As well, when the system is unexpectedly loaded, a “startle response” is induced. Thus, the spine acts as a second order system and overshoots a response to the perturbation, which magnifies the spinal loading, as a mechanism to increase the stability of the trunk (Lavender et al., 1993).

Lateral perturbations also induce unique muscle recruitment patterns during anticipatory postural adjustments, compared to symmetrical perturbations. Asymmetric
loading of the spine, characterized by the moment direction and the asymmetrical muscle recruitment, has been identified as a risk factor for low-back injuries (Lavender, Chen, Trafimow and Andersson, 1995). Asymmetric loading conditions, in combination with sudden loading, are assumed to magnify the adverse main effects of each condition and result in extreme loading of the lumbar spine. In asymmetric loading conditions, flexion, and/or axial twisting of the trunk most often accompanies lateral bending. As stated, lateral perturbations evoke unique muscle recruitment patterns during anticipatory postural adjustments, as compared to similar symmetrical perturbations. This may be due to the complex moment placed on the spine during asymmetrical loading which has a forward and/or lateral bend component (Schultz, Andersson, Haderspeck, Ortengren, Bjork et al., 1983; Zetterburg, Andersson and Schultz, 1987; Marras and Mirka, 1989). As a result of the recruitment of individual trunk muscles that are necessary to stabilize the spine and resist an asymmetric load, there is an increase in compressive forces at the lumbar spine (Lavender, Mirka, Schoenmarklin, Sommerich, Sudhakar et al., 1989; Lavender, Tsuang, Andersson, Hafezi and Chaffin, 1992a).

To re-iterate, whole-body equilibrium and trunk stability are both of paramount importance to the maintenance of vertical upright posture and the performance of activities of daily living. Research studies have concentrated on the control of trunk stability in isolation, without whole-body posture consequences, and whole-body postural control solely as a motor control phenomenon. It is the intent of this study to investigate the integration of whole-body control of equilibrium and trunk stability within the theoretical framework that spine instability is a mechanism of low-back injury. It is ultimately the combination of whole-body equilibrium and trunk stability that results in
the successful execution of goal-directed movements, which are characterized by the appropriate anticipatory postural adjustments. The question remains as to whether whole-body equilibrium and trunk stability are separate entities to voluntary motor commands or rather inherent of voluntary motor commands. To investigate the extent of the relationship between whole-body posture control and trunk stability, tasks with varying levels of load timing and complexity (Symmetrical versus Asymmetrical) will be studied. This provides the rationale for the focus on the anticipatory activation of postural muscles and postural adjustments involved with whole-body postural preservation and trunk stability in the present study.

Purpose

The purpose of this study was to examine whole-body and trunk posture control to sudden loading at the hands, with a special focus on the implications of loading to spine stability. The effects of load symmetry were investigated in combination with anticipation.
Hypotheses

Load Symmetry

1. When loading asymmetrically to the right side, the left lumbar and thoracic erector spinae (LES and TES) and external oblique (ExO) agonistic trunk muscles, will respond with higher activation. The right side internal oblique (InO) and ExO, which are antagonistic, stabilizing muscles of the trunk, will exhibit a higher peak muscle activity, relative to the Symmetrical loading conditions. Under Asymmetric conditions the time to peak onset latency will be longer versus the onset latencies in the Symmetrical loading condition.

The Asymmetrical load will always be delivered to the subject’s right. This will generate both a forward flexion and a right lateral bend of the trunk. As a result, the trunk muscles on the left side will be required to generate an increased agonistic activity to resist the lateral bend. The antagonistic trunk muscles on the right side of the body will be activated to maintain the upright posture and trunk stability (Lavender et al., 1992a; Lavender et al., 1995; Thomas et al., 1998). The longer time to peak onset latency is a result of the complex muscle recruitment patterns predicted in Asymmetrical loading conditions.

2. During Asymmetrical loading, the leg muscles will respond with an increase in the muscle activity of biceps femoris (BF) and soleus (Sol) on the right side of the body, relative to muscle recruitment patterns in the Symmetrical loading condition.

An increase in the right side lower extremity muscles will resist the laterally induced moment applied in the asymmetrically applied load.
Anticipation of Loading

3. Peak muscle co-contraction activation levels, in response to the sudden, unexpected perturbation, will be higher than those evoked in the Symmetric condition.

When the time-to-load onset is unexpected, the synergistic/antagonistic muscle pairs in the trunk and legs will co-contract to increase stabilization compared when the load onset is expected. Marras et al. (1987) quantified that the Unexpected condition produced greater peak muscle activity of the agonist and antagonist trunk muscles, than the Expected condition.

4. In the Unexpected loading condition, there will be a shorter time-to-peak latency for both the agonist/antagonist trunk and lower extremity muscles, compared to the Expected timing condition.

The average baseline muscle activation levels of the agonist/antagonist trunk and leg muscles will exhibit pre-activation levels, as hypothesized above. This co-contraction is a preparatory strategy to prepare for the sudden loading. Marras et al., (1987) and Thomas et al., (1998) both measured a greater time to peak activation in the Unexpected, relative to the Expected condition.

5. The APAs will be smaller in the Unexpected condition when compared to the Expected condition.

In the Unexpected loading condition, the overall postural disturbance will not be reduced, relative to perturbations that are expected (Lavender et al., 1993). It is assumed that there will be insufficient warning time to generate an APA prior to load onset, in the Unexpected condition.
Interaction of Asymmetry and Expectation

6. The hypothesized differences between the Expected and Unexpected conditions will be more pronounced in Asymmetrical loading conditions.

Asymmetrical loading conditions are considered to evoke a more destabilizing perturbation, relative to symmetrical loadings (Lavender et al., 1992a; Kingma et al., 1998; Thomas et al., 1998). It is hypothesized above, that asymmetric conditions will yield higher peak agonist/antagonist muscle activity to stabilize the trunk, as compared to Symmetrical conditions. Unexpected loading also results in a greater co-activation response, to increase trunk stability, as compared to expected conditions when the time-to-load onset is presented (Thomas et al., 1998). It is hypothesized that the effects of Unexpected loading will be magnified in the Asymmetrical conditions.

7. In the Expected loading condition, contrary to the Unexpected condition, the APA will be increased in the medial-lateral (ML) direction under Asymmetrical versus Symmetrical loading.

It is hypothesized that the APA will increase in the ML direction to compensate for the lateral component of the perturbation, which is unique relative to the Symmetrical condition (Wu and MacLeod, 2001). It is proposed that an interaction exists between Expected loading and Asymmetrical conditions. This is a result of the instability that is inherent in the Asymmetrical conditions leading to magnified effect of Expected loading.
Chapter 2

REVIEW OF LITERATURE

Postural Control

Fundamental Role of Balance in Voluntary Dynamic Movements

"The fact that humans are able to maintain vertical posture is by itself a miracle" (Latash, 1998). It is not possible to skillfully perform many ADL, some as simple as pouring a glass of water, without adequate postural control. Voluntary movements, also referred to as focal or goal-directed movements, are virtually always associated with changes in the activity of postural muscles and subsequent balance control strategies (Bouisset and Zattara, 1981; Cordo and Nashner, 1982; Brown and Frank, 1987; Crenna, Frigo, Massion and Pedotti, 1987; Lee, Buchanan and Rogers, 1987). Humans typically execute tasks almost automatically without being aware that certain body segments, or the equilibrium of the whole body, is actually being controlled throughout the task.

Balance is indispensable for the successful execution of all of the manipulative tasks performed during upright stance (Massion, 1992) in which the voluntary arm movement itself imposes a threat to balance. Such perturbations or disturbances of posture occur when the equilibrium of the whole body is affected by muscle forces and angular moments that are generated to execute the focal movement (Oddsson and Thorstenson, 1986; Bouisset and Zattara, 1987; Massion, 1992, 1994). To maintain equilibrium, additional postural muscles are recruited to stabilize the affected joints (Commissaris, 1997; Latash, 1998). It is well documented that there are preprogrammed
combinations of motor commands to regulate the muscle activity of the lower extremities and trunk which are designed to maintain postural orientation in the event of an external perturbation (Nashner, 1977; Horak and Nashner, 1986).

Biomechanical Principles

Equilibrium is maintained by generating muscle forces to counteract all other forces acting internally or externally on the body. Equilibrium is the mechanical component that necessitates the fulfillment of mechanical conditions such as projection of the body's centre of mass (CoM) within the base of support (BoS). The CoM is a point equivalent of the total body mass that vertically projects on the ground (Winter, 1995). The BoS is the area defined by the maximal transverse distance between the left and right margins of the feet in contact with the ground (McIlroy and Maki, 1993b). Increased support surface area, subsequently the BoS, results in an increase in postural stability (Do, Noillot and Bouisset, 1991). A fundamental goal of postural equilibrium is the control of the position and velocity of the trunk in space, as two-thirds of the body weight is located above the hips (Massion, 1994; Horak and MacPherson, 1997). In upright stance, postural equilibrium requires the CoM to be positioned over the BoS, although the linkage is inherently unstable because of the force of gravity acting on the body (Massion, 1994; Maki and McIlroy, 1997; Latash, 1998). Additional destabilizing forces arise due to movements of body segments and interactions with the environment. Posture is defined as the overall body orientation and is a composite of segmental postures that are each under neurophysiological control (Do et al., 1991). Posture and equilibrium are not mutually exclusive and it is hypothesized, that contrary to previous
belief, both may be regulated by the same neural pathways. For the central nervous system (CNS) to facilitate smoothly coordinated movements and maintain balance and equilibrium, it must estimate and anticipate the various forces acting on the body. It is the generation of active muscle forces in combination with all the external and indirect forces that give rise to movement. Postural control provides a stable body platform for the efficient execution of focal movements.

Postural Strategies

Postural adjustments for maintaining orientation and equilibrium arise from neural strategies that are directed by complex sensorimotor control processes. Initially the CNS has the functional role of organizing all the context dependent constraints that are associated with maintaining balance. This convergence of sensory information is processed to determine the timing, direction and amplitude of the corrective postural response (Nashner, 1982). Corrective postural responses involve neuromuscular strategies that generate supportive reactions. Coordinated muscle responses are characterized by temporal sequencing and recruitment patterns of the trunk and lower extremities (Nashner, 1982). Postural strategies are then evoked consisting of preprogrammed neuromuscular plans with a goal of maintaining postural equilibrium and orientation. Neural control of posture has been demonstrated when the focal movement involves a displacement of the CoM with respect to the BoS, usually in the horizontal direction (Cordo and Nashner, 1982; Bouisset and Zattara, 1987; Massion, 1992), or as imposed by voluntary upper limb or trunk movement (Brown and Frank, 1987; Crenna et al., 1987; Oddsson, 1990). Examples of postural strategies in the control of balance
during stance are the ankle and hip strategies. The ankle strategy is predominating in quiet stance and during small perturbations, as the ankle synergistic plantarflexors and dorsiflexors (TA-Sol) act primarily alone to control stability. In a more perturbed condition, the hip strategy would respond to either flexing the hips, thus displacing the CoM posteriorly, or to extending the hips to anteriorly displace the CoM (Winter, 1995). These combinations of muscle recruitment patterns for a given magnitude and directional perturbation are termed “postural strategies” (Diener, Dichgans, Bootz and Bacher, 1984, Nashner and McCollum, 1985).

Two different control mechanisms, termed “predictive” and “reactive”, have been defined to describe the link between posture and movement coordination. Predictive, or feed-forward control consists of preprogrammed muscle synergies, which generate the necessary forces or moments to counteract external or internal forces arising from moving segments. Predictive balance control anticipates, and compensates for, the destabilization caused by task execution or induced by a perturbation prior to their occurrence. The definitive example of an important predictive balance control mechanism is the anticipatory postural adjustment (APA) that is the subject of the following chapter.

Responses regulated by reactive or feedback controls are generated in response to disturbances in stability. This type of control also involves preprogrammed postural or axial synergies. Postural synergies are coordinated, opposing displacements of upper and lower body segments that minimize CoM displacement during forward and backward trunk bending (Crenna et al., 1987; Oddsson, 1988; Alexandrov, Frolov and Massion, 1998). Reactive responses are stereotypically complex short-latency reflexes, which are

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initiated in response to a perturbation. Research paradigms have used reactive responses to external disturbances during standing to investigate conflicts between sensory systems in the control of balance. Examples are the classical stretch reflexes evoked in response to a moveable platform (Nashner, 1977), hip or ankle strategies generated as an attempt to restore balance in response to platform perturbations (Nashner and McCollum, 1985), or compensatory stepping in response to platform translations (McIlroy and Maki, 1995; Maki and McIlroy, 1997).

Voluntary dynamic movements most often feature a combination of anticipatory and reactive controls that are facilitated concurrently with ongoing movement. Postural control and whole body equilibrium ensures the smooth execution of many activities of daily living.

Anticipatory Postural Adjustments

Anticipatory postural adjustments (APAs) are changes that occur prior to the equilibrium disturbances that are caused by the focal movement itself (Massion, 1992). An APA is a predictive mechanism of postural control, which acts to minimize the destabilizing effects of the forthcoming movements in order to maintain the body in a state of equilibrium (Bouisset et al., 2000). These feed-forward commands have been interpreted as generating the necessary forces and moments to counteract the external or internal forces arising from mobile segment(s), thus minimizing CoM perturbations (Bouisset and Zattara, 1981, 1987). It is widely accepted that APAs are distinguished as postural movements in the opposite direction of the anticipated perturbation (Bouisset
and Zattara, 1987). Anticipatory postural muscle activation occurs either simultaneously or prior to the disturbance (Massion, 1992). With the addition of an external support to either the whole body or individual segments, anticipatory postural activity is reduced (Cordo and Nashner, 1982).

Evidence of anticipatory dynamics of voluntary movements has been well documented for lower extremities (Rogers and Pai, 1990; McIlroy and Maki, 1993a; McIlroy and Maki, 1995; Burliegh and Horak, 1996; Mille and Mouchino, 1998), pushing and pulling a handle (Cordo and Nashner, 1982), flexion/extension movements of the trunk (Oddsson and Thorstenson, 1986; Crenna et al., 1987), movements of the whole body (Massion, 1992; Commissaris and Toussaint, 1997b; Toussaint, Commissaris, Hoozemans, Ober and Beek, 1997; Stapley, Pozzo and Grishin, 1998) and upper extremities (Belenkskii, Gurfinkel and Pal’tsev, 1967; Bouisset and Zattara, 1987; Brown and Frank, 1987; Aruin and Latash, 1995a). This research has shown an important relationship between the characteristics of the APA and the voluntary focal task, which it precedes or resists.

*Dynamic Whole-Body Lifting*

Dynamic whole body lifting is an example of a voluntary multi-joint movement that has a well-documented APA. Commissaris (1997) focused on whole body lifting as both the trunk and lower extremities serve a functional role in focal movements and postural adjustments. Lifting causes a displacement of the CoM with respect to the BoS, which affects equilibrium and must be regulated to ensure successful execution of the task goal (Crenna and Frigo, 1991). A forward CoM displacement with respect to the
BoS implies dis-equilibrium and active control of the horizontal CoM position is assumed in equilibrium regulation. Initially, whole body equilibrium is challenged by the forward and backward bending of the upper body inducing a considerable forward-backward displacement of the CoM in the absence of an adequate APA. The second challenge in the maintenance of equilibrium is the additional mass being picked up in front of the body also causing a forward shift of the CoM. The inertia of the grasped object decelerates the backward extension moment of the lumbar spine necessary to return the trunk (whole body) towards a final erect posture and state of equilibrium (Touissant et al., 1997).

Commissaris and Touissant (1997b) revealed that APAs in bimanual load lifting tasks were aimed at minimizing the destabilizing effect of load pick-up. Biomechanical analysis determined that the centre of pressure (CoP) or ground reaction force (GRF) vector is applied substantially in front or behind the CoM generating an external (angular) moment about the ankle (Commissaris, 1997). Centre of pressure (CoP) is defined as the point location of the vertical GRF vector that represents the summed total of pressure in contact with the ground (Winter, 1995). This contradicts original assumptions that the CoP was aimed directly at the CoM (Nashner and McCollum, 1985). Ingen Schenau, Boots, Groot, Snacker and Woensel (1992) demonstrated that the muscle activation patterns of the lower extremities are coordinated to regulate the direction of the CoP. The CoP was demonstrated to be directly related to the torque about the ankle joint (Touissant, Commissaris, van Dieen, Reijen, Praet et al., 1995). The combination of joint torques yields a forward CoP shift that is associated with an anticipatory increase in the backward direction GRF vector, relative to the ground. The whole body angular
momentum about the ankle joint is regulated by the moment exerted by the GRF vector about the CoM location. The crucial role of ankle synergistic muscle pairs associated with the control of equilibrium in static tasks is the control of the amount of rotation of the whole-body (a dynamic parameter) about the ankle joint (Horak and Nashner, 1986; Oddsson and Thorstenson, 1986; Aruin and Latash, 1995a). APAs also generate an increase in the external (angular) momentum about the ankle, which consequently decreases the forward rotational velocity of the trunk that affects stability during lifting tasks. This indicates that APAs are dependent on the velocity of the forthcoming movement (Bouisset and Zattara, 1981).

*Attenuation of APAs*

Modulation and intensity of the APA are scaled as a function of the dynamic requirements of the motor task (Nashner and Forssberg, 1986; Bouisset and Zattara, 1987; Oddsson, 1990; Hirschfield and Forssberg, 1991). Struppler, Gerilovsky and Jakob (1993) demonstrated that if a perturbation were induced in a predictable and external manner, an APA would not be evoked. However, the motor actions of self-induced triggers continually produced APAs that were scaled to the magnitude and direction of the expected postural perturbation (Lee, Michaels and Pai, 1987; Struppler *et al.*, 1993; Aruin and Latash, 1995b). Thus, the magnitude of the motor action triggering a perturbation and the magnitude of the perturbation each affect APAs independently. Aruin and Latash (1996) confirmed that the CNS is capable of providing adequate postural adjustments in response to changes in the magnitude of a perturbation, even if the magnitude of the triggering action does not change.
In early studies APAs have been described in terms of electromyographic (EMG) activity where APA amplitudes and APA durations have been considered separately (Kasai and Kawai, 1994; Aruin and Latash, 1995b). Postural synergistic muscle pairs were activated prior to the focal movement; specifically proximal muscles exhibited the largest decrease in background activity. Changes in activation of distal muscles were associated with anterior-posterior movements; these ankle muscles are proposed to be responsible for fine postural adjustments (Aruin and Latash, 1995b). Bouisset et al. (2000) revealed that APA amplitude and duration are scaled according to the same focal movement parameters, while APA duration is attenuated to a greater degree by the postural goal of the focal movement.

Postural stability and/or static and dynamic conditions of the task are the last factors affecting the process of the generation of APAs. The relationship between the predictive APA adjustments appears to be strongly dependent on the magnitude of balance stability of the postural task (Do et al., 1991). APAs are themselves a perturbation to the initial equilibrium. Nouillot, Bouisset and Tuma (1992) suggested that when postural equilibrium is unstable, APAs are absent. It is possible that the exclusion of a postural adjustment in these trials is necessary to allow time for rapid generation of a compensatory stabilizing reflex, by eliminating the additional time required for the generational of the functional APA. This is supported by results from McIlroy and Maki (1993b) who observed reduced reflexive muscle latencies in the range of 100 ms when an APA was excluded prior to compensatory stepping response. In conditions of high stability demands, the CNS suppresses APAs as a protection against their possible destabilizing effects. It is proposed that these effects are more pronounced
when the directions of an expected perturbation and the instability coincide (Aruin, Forrest and Latash, 1998).

**Leading Organizing Principle of APAs**

The cumulative effect of these factors influencing the generation of APAs poses the need to identify the leading principle in organizing postural adjustments. Massion (1992) originally theorized that the leading principle regulated by postural adjustment was the stabilized position and minimized displacement of the CoM within the BoS. This assumption has been highly recurrent in the literature, especially under static conditions. Yet in recent research, the use of CoM displacement as a stabilized reference value, for both posture and movement has been invalidated (Touissant et al. 1997; Commissaris, 1997; Stapley et al., 1998; Stapley, Pozzo, Cheron and Grishin, 1999; Stapley, Pozzo, Grishin and Papaxanthis, 2000). Commissaris (1997) and Touissant et al. (1997) determined that during whole-body forward reaching and lifting movements, APAs were characterized by changes in the external moment about the ankle joint. The external moment is regulated by the moment exerted by the GRF vector about the CoM. The control of the amount of rotation of the whole-body appeared to take precedence over the control of the horizontal CoM position. In this context APAs did not act solely to stabilize the CoM. Stapley et al. (2000) examined the feasibility of fixing the CoM position within the BoS while executing a whole-body reaching task. APAs facilitated changes in joint torques necessary to complete the task, although the results of this study did not support the CoM as the stabilized reference value (Commissaris, 1997; Stapley et al., 2000). As pointed out above in the example of APAs in whole-body lifting, CoP
(whole-body angular momentum) is regarded as the crucial variable in the control of movement and equilibrium. Adjustments of whole body angular momentum largely reflect trunk/head orientation. The fundamental need to control the (angular) position of the trunk is well established (Latash, 1998). Gurfinkel, Lipshitis, Mori and Popov (1981) demonstrated that the trunk position was the main parameter regulated in the maintenance of the vertical posture against a perturbation.

A commonly accepted theory is that voluntary, focal movement and posture is controlled by two separate pathways (Massion, 1992). Such a theory is not applicable to whole-body lifts, in view of the fact that postural segments (lower extremities) participate in the focal aspect of the movement and APAs, creating the necessary dynamic conditions for task stability. The strict dichotomy of the control of posture and movement that has been widely accepted is now being questioned. Oddsson, Persson, Cresswell and Thorstensson (1999) hypothesized that postural adjustments may not be a mere addition to a voluntary motor command, but rather an inherent part of it. This suggests that one common postural and neural pathway may be responsible for both postural and focal movements.
Stability of the Spine

Stability of the lumbar spine is an important factor in determining the whole body’s response to induced perturbations and maintaining postural equilibrium. Trunk stability has been of keen interest due to its direct correlation with low-back pain (LBP). Low back pain is a well-recognized problem of epidemic proportions, which results in substantial social loss (Leamon, 1994). With the enormous amount of money being lost, and pain being suffered, it is essential that the etiology and mechanisms of injury be determined.

From a mechanical viewpoint, Bergmark (1989) defines stability as “the ability of a loaded structure to maintain static equilibrium even at small fluctuations around the equilibrium position”. Crisco and Panjabi (1992) provide the analogy of a column that returns to its vertical position after it has been perturbed by some force. The load at which the column buckles is said to be its “critical load”. However, the spine is not strictly a mechanical system, but also a complex biological system. Spinal stability involves the neuromuscular coordination and recruitment of a vast number of muscles, both inter-segmental and multi-segmental. A general assumption made is that muscle recruitment strategies are based upon minimizing physiological costs associated with function (Gardner-Morse and Stokes, 1998). Evidence to the contrary will be presented in the following review.

Bergmark (1989) theorized that mechanical stability was achieved through muscle stiffness. Critical stiffness is defined as the minimum stiffness required to maintain stability for a perturbation of a given magnitude, and to prevent buckling of the spinal
stability system (Crisco and Panjabi, 1991). In the human spine, stiffness is modulated by muscular activity (Rack and Westbury, 1974). It is hypothesized that muscle stiffness is regulated by the neuromuscular system by setting agonist/antagonist muscle activation and co-contraction recruitment patterns to ensure lumbar stability (Bergmark, 1989; Crisco and Panjabi, 1991; Gardner-Morse, Stokes and Laible, 1995). A lower range of stiffness is proposed to be sufficient, as this enables the system to respond rapidly when perturbed. Short-latency reflexes or APAs are an example of the system's rapid response. Cholewicki and McGill (1996) suggest that the neuromuscular system does not maintain a constant level of spinal stability, but rather that spinal stability is task specific.

Mechanical stability is necessary to perform the fundamental functions of the spine such as: dynamic movements between body parts, carrying of external loads and the protection of the spinal neural system. Panjabi (1992a) has proposed that spinal stability is controlled by three subsystems: a control subsystem, a passive subsystem and an active subsystem. The passive subsystem is not an active proponent in generating spinal movements to meet stability requirements, but rather monitors the neutral posture. This subsystem is composed of ligaments, vertebrae and intervertebral discs. In the neutral posture these components act as transducers, measuring vertebral positions and movements. Feedback requirements for spinal stability are forwarded to the muscle force generators, which serve as the active subsystem. Skeletal muscles are responsible for generating the moments that resist and cause movement. Feedback from the passive and active systems is relayed to the neural control system. This subsystem is responsible for coordinating neuromuscular strategies that define muscle recruitment, timing and muscle force generation patterns necessary to achieve stability, control posture and movement.
The active system also interacts with the neural subsystem by returning information such as muscle tension and length, through muscle tendons, which act as force transducers. Normal function of the stabilizing system is dependent on each of the subsystems functioning and interacting appropriately.

**Concept of Neutral Zone in Spine Instability**

The stabilizing function of the trunk musculature is of importance, especially in neutral postures, as the spine has a high degree of flexibility with minimal contribution of muscular activity (Cholewicki, Panjabi and Khachatryan, 1997). This illustrates the concept of the neutral zone, a region of low stiffness about neutral posture, first introduced by Panjabi (1992b). The neutral position is defined as, “the posture of the spine in which the overall internal stresses in the spinal column and the muscular effort to hold the posture are minimal”. The stability in the neutral posture, without additional external loads, is imperative as it is maintained throughout the duration of an entire day. Cholewicki and McGill (1996) have indicated that because of the low levels of muscle activity in this position, the lumbar spine is especially vulnerable and at risk of buckling upon being perturbed. The work of Cholewicki *et al.* (1997) quantified the role of trunk flexor-extensor co-activation about the neutral position. A low level of antagonistic co-activation was recorded (less than 2% MVC) during slow trunk flexion-extension tasks around the neutral posture. It was concluded that co-activation increases stiffness about the spinal column to assure mechanical stability about the neutral posture.
Muscle Force and Muscle Stiffness

In the sliding filament theory, muscle tension is thought to be the result of the interaction between the actin and myosin cross-bridges, which maintain spring-like properties (Hansen and Huxley, 1955; Huxley, 1957). Rack and Westbury (1974) proposed that the short-range stiffness of a muscle was defined by the properties of the cross-bridge within a given muscle. An increase in stiffness was correlated with an increase in muscle tension. The proposed relationship is rationale in that both muscle stiffness and tension are based upon number of myofilament cross-bridges. Thus, it is recognized that intrinsic active muscle stiffness is proportional to contractile force.

The Role of Trunk Musculature in Spinal Stability

The spinal column, devoid of musculature, is incapable of resisting physiological loads imposed on it. Adequate muscle function is required to stabilize the spine within its normal biological movements. In 1961, Lucas and Bresler demonstrated that an isolated spine buckles under a mere 20 N compressive load. The lumbar portion of the spine has been shown to collapse under an axial load of 90 N (Crisco, Panjabi, Yamamoto and Oxland, 1992). These loads are only a small percentage of the total cumulative loading that the trunk experiences during the performance of activities throughout any given day. This re-iterates the importance of the neuromuscular system in maintaining spinal stability. Aside from generating force, the role of the trunk musculature is to act as stabilizing springs and serve as active modulators of stiffness. Increases in the intensity
of muscle activation are proportional to increases in stiffness, which can prevent the lumbar spine from buckling (Cholewicki and McGill, 1996; Cholewicki et al., 1997; Gardner-Morse and Stokes, 1998). Gardner-Morse et al. (1995) propose that muscle stiffness alone is inadequate to maintain spinal stability in response to perturbations and low-back injury may be incurred in the conflict between equilibrium and stability.

Figure 1: The abdominal musculature (only right side shown). A: External Oblique, B: Internal Oblique. From Stone and Stone, 1990.
Figure 2: The posterior trunk musculature. A: left and right thoracic lumbar erector spinae, B: left lumbar erector spinae. From Bogduk and Twomey, 1987.

Panjabi, Abumi, Duranceau and Oxland (1989) speculated that lumbar stability was the result of the deep, medial inter-segmental muscle forces. The short muscle length was speculated to decrease reaction time, consequently increasing response time, which would enable the neuromuscular system to efficiently fine tune stability. In addition, the location near the vertebral column also facilitates an efficient and smooth response to feedback from neural control. Crisco and Panjabi (1991) later challenged this theory and modeled the lateral stabilizing potential of inter-segmental and multi-segmental muscles. They found that larger, pelvic-originating multi-segmental muscles were more efficient (i.e. requiring lower muscle stiffness) at stabilizing the spine. These muscles were better adapted to counterbalance external loads and to achieve overall spinal posture and movement.
Aside from the stiffness associated with increased muscle activation, increased antagonistic trunk muscle activity leads to joint compression. Several researchers have noted the effect of joint compression and co-activation on mechanical stability (Bergmark, 1989; Crisco and Panjabi, 1991; Gardner-Morse et al., 1995). Cholewicki and McGill (1996) demonstrated that increased moment demands and increased joint compression on the trunk leads to greater stability. Quint, Wilke, Shirazi-Adl, Parnianpour, Loer, et al. (1998) examined the recruitment of synergistic muscle pairs as a strategy for stability resulting in increased lumbar compressive forces. Co-activation of psoas and multifudus muscles was reported to increase the overall stiffness (stability) of the inter-vertebral joints in axial torque and lateral bending. Bergmark (1989) has also attributed some stabilizing potential to the abdominal musculature. Abdominal co-activation has been confirmed to increase spinal stability, yet Gardner-Morse and Stokes (1998) indicated that this is at the cost of increased muscle fatigue rates and increased spinal compression. The neuromuscular system is obligated to assess and balance trunk stability, muscle fatigue and the magnitude of lumbar spinal joint compression. Although this antagonistic muscle activity evokes higher metabolic demands and decreases net moment generation, it is hypothesized that co-activation is imperative to trunk stability (Seroussi and Pope, 1987; Panjabi et al., 1989, Cholewicki and McGill, 1996; Gardner-Morse and Stokes, 1998).
Intra-Abdominal Pressure

Intra-abdominal pressure (IAP) has also been considered as a mechanism for increasing spinal stability (Cholewicki, Juluru and McGill, 1999). Cresswell et al. (1994) state that abdominal muscles forcefully contract against the pressurized peritoneal cavity, stabilizing the trunk and spine. Research evaluating the effect of IAP on spinal loading has produced inconsistent results. Marras and Mirka (1996) have correlated the onset of torque development at the lumbar spine with rises in IAP. In a study quantifying preparatory strategies to sudden loading, Lavender et al. (1993) indicated that IAP was responsible for trunk acceleration. Cresswell et al. (1994) also noted an increase in abdominal muscle activation and IAP prior to sudden loading perturbation. A possible explanation is that the compressive forces of the contracting abdominal muscle cancel out the hydrostatic IAP force adversely acting on the lumbar spine, resulting in negligible forces and moments influencing the spine. Thus, increased abdominal activation is what actually produces the stabilizing phenomenon. However, Cholewicki et al. (1999) state that it is likely that both mechanisms, abdominal muscle activity and IAP, combine to stabilize the spine.

In summary, the spinal column is inherently unstable. The neuromuscular coordination of active and passive components results in muscle recruitment responses, which stabilize the spine. As a whole, it appears that the trunk musculature contributes to spinal stability through primarily two mechanisms: modification of muscle stiffness (Crisco and Panjabi, 1991; Crisco and Panjabi, 1992); and contributing to spinal compression via antagonistic muscle co-contraction or IAP (Cholewicki and McGill,
Sudden Loading to the Spine

Stability of the spine is an intrinsic component and prerequisite to whole body equilibrium and postural control. Adequate control of trunk movement and spinal stability are necessary for successful execution of motor tasks as simple as upright stance. As stated, two-thirds of the body weight is located above the hips, which reaffirms the importance of trunk stability. Upon a perturbation being imposed on the system, the neuromuscular response is designed to minimize the destabilizing postural disturbance and mechanical loading on the spine (Lavender et al., 1993). Epidemiological research has cited perturbations to the trunk to be correlated with the incidence of low-back injury (Andersson, 1981; Frymoyer, Pope, Clements, Wilder, MacPherson et al., 1983). Magora (1973) and Andersson (1981) concluded that there is a predisposition for occupations that require sudden maximal physical efforts in response to unexpected loading. Conditions of sudden, unanticipated loading evoke an under damped, over-reactive response from the spine (Magora, 1973; Manning et al., 1984; Marras and Mirka, 1989; Magneusson, Aleksiev, and Wilder, 1996). The increased muscle activity associated with unexpected perturbations elicits increased compressive loads on the lumbar spine, and increased risk of injury (Lavender et al., 1993).
Sudden loading to the spine is defined as an involuntary force that perturbs the system, causing the trunk to deviate and/or displace towards the direction that has been loaded, subsequently evoking compensatory responses to regain stability. This sudden response from the neuromuscular system results in increased biomechanical compression and shear forces (i.e. mechanical loading) on the lumbar spine (Marras and Mirka, 1989; Lavender et al., 1993; Cresswell et al., 1994; Thomas et al., 1998). To maintain stability, trunk musculature must compensate by altering activation patterns. Because of the multiple degrees of freedom and mechanical redundancy, both in structure and function, the neuromuscular control of the spine is extremely complex. Consequently, the stabilizing response to sudden loading depends on sufficient muscle force, efficient muscle recruitment and coordinated timing patterns to ensure mechanical stability of the spine (Gardner-Morse et al. (1995) in Radebold, Cholewicki, Panjabi and Patel, 2000; Cholewicki et al., 1997).

Initially the dynamic manner, in which the sudden external force is applied, necessitates an additional muscle force to counteract the disturbance to postural equilibrium (Carlson, Nilsson, Thorstensson and Zomlefer, 1981; Marras, Rangarajulu and Lavender, 1987; Lavender et al., 1993; Wilder, Aleksiev, Magnusson, Pope, Spratt et al., 1996). In a study by Marras et al. (1987) the magnitude of peak trunk muscle responses was 35% greater in a sudden loading condition, as compared to that required to resist a load of the same magnitude under static conditions. This result demonstrates the effect of dynamic loading. A second compounding factor is the over-compensatory responses due to the unanticipated nature of the perturbation that result in increased spinal compression forces.
As indicated, expectancy surrounding the temporal occurrence of a perturbation significantly affects the magnitude of the response (Cresswell et al., 1994; Lavender and Marras, 1995). Lavender and Marras (1995) investigated the effects of a temporal warning signal on preparatory strategies in the event of sudden loading. Onset rate of muscle force exertion levels and duration of elevated muscle force exertion levels are far more exaggerated in unanticipated conditions. Greenwood and Hopkins (1976) used the term “startle response” to describe the large burst of muscle activity as subjects were loaded unexpectedly. Mannion, Adams and Dolan (2000) reported that unexpected loading yielded a 30 to 70% increase of peak spinal loads, peak onset and duration latencies for maximal muscle activity. Both dynamic and unanticipated components of the load accentuate spinal loading evoking an under damped and over-compensatory response, thereby increasing the risk of injury.

Oddsson et al. (1999) found that a sudden external perturbation to equilibrium during a dynamic voluntary forward flexion movement, elicited a conflict between postural and focal motor commands. Both postural adjustments and the primary movement required simultaneous, yet individual, activation of the erector spinae muscles. This conflict of rapid switching between motor and functional programs causes large fluctuations in the activation of the trunk musculature and is hypothesized to be a mechanism of LBP.

Preparatory strategies have been demonstrated with anticipated or learned perturbations and are less likely to trigger the sudden exertions that are associated with LBP onset. With knowledge of load onset, muscle recruitment patterns and whole body kinematics are adjusted to counteract the anticipated perturbation. APAs have been
established as individuals responded to perturbations affecting the body’s postural stability (Cordo and Nashner, 1982; Bouissett and Zattara, 1987; Lavender et al., 1989). To counter the expected forces and moments coupled with the upcoming perturbation, the APA evoked changes in the CoM displacement and kinematics. Anticipation also implicates neuromuscular coordination of stability. Lavender et al. (1993) reported that muscle recruitment increased trunk extensor activation to increase stiffness under sudden, unexpected loading conditions. Anticipated trunk muscle responses result in increased spinal stability and reduced lumbar spinal compression forces. Preparatory EMG responses recorded by Bouissett and Zattara (1987) were analogous to a pretension strategy and co-contraction of antagonistic muscle pairs of both trunk and lower extremity musculature. Abdominal muscle co-contraction has also been rationalized as a stabilizing mechanism in anticipation of a sudden, unexpected perturbation. Anticipatory synergistic/antagonistic co-activation is reported in several studies (Lavender et al., 1989; Marras et al., 1987).

Asymmetric Perturbations

Several research studies have focused, on and modeled, the body’s response to an external load resisted in the sagittal plane. Complex muscle responses have been identified to asymmetric perturbations (Schultz et al., 1982; Zetterburg et al., 1987; Marras and Mirka, 1989), as opposed to those where the perturbation is applied symmetrically and subsequent load distribution is equal between the right and left sides of the body. Lateral bending and twisting postures have been identified in
epidemiological studies as correlated in the incidence of LBP (Punnet, Fine, Keyserling, Herrin and Chaffin, 1991; Marras, Lavender, Leurgans, Rajulu, Allread et al., 1993). Asymmetric loading of the spine, created by a non-sagittally symmetric perturbation, evokes asymmetric muscle recruitment in response to lateral bending. It is hypothesized that the asymmetric loading, and consequent imbalance of muscle recruitment patterns, are mechanisms of injury (Lavender, Chen, Trafimow and Andersson, 1995). Inevitably, asymmetric working postures are considered more stressful. Asymmetric loading conditions, in combination with sudden loading, is assumed to magnify the main effects of each condition and result in extreme loading of the lumbar spine. Thomas et al. (1998) reported that asymmetric loading of the torso resulted in an increase in peak and mean EMG responses of contralateral trunk musculature and a decrease in the ipsilateral muscle activation. However, muscle responses in different experimental paradigms reveal discrepancies between the activation of ipsilateral and contralateral abdominal muscles (Carlsoo, 1961; Schultz et al., 1982; Zetterburg et al., 1987). Lavender et al. (1989), et al. (1992a) and Thomas (1998) found that both posterior and anterior trunk muscles displayed longer peak latencies and were activated simultaneously. This may be due to the complex moment placed on the lumbar spine during asymmetric loading. An asymmetrical load applied to the spine yields lateral bending of the trunk. Lateral bending of any degree results in rotations in coupled flexion-extension and axial movements (Lovett, 1905; Percy and Tibrewal, 1984).

The trunk is required to generate high erector spinae (ES) muscles forces to resist forward and/or laterally induced moments triggered by sudden, asymmetric loads (Lavender et al., 1989). Counterbalancing of external, mainly flexing moments on the
trunk requires high ES muscle forces because of its comparatively small lever arm (van Dieen, 1996). Increased activation of ES, usually the agonist muscle contralateral to the direction of the applied load, reaches higher peak EMG in unexpected conditions (Lavender et al., 1992a; Kingma, van Dieen, de Looze, Touissaint, Dolan et al., 1998; Thomas et al., 1998). Many studies have quantified the elevation of activity in the contralateral lumbar ES to neutralize the lateral bending moment in the frontal plane, and little increase in the activity of ipsilateral lumbar ES to generate a sagittal external moment (Schultz et al., 1982; Zetterburg et al., 1987; McGill, 1992; Lavender et al., 1993). Postures assumed during work tasks frequently involve maintaining laterally deviated postures that evoke asymmetric patterns in muscle recruitment. Lavender et al. (1995) concurred with previous research in that the greatest response of both contralateral external oblique (ExO) and ES was recorded when the load was applied asymmetrically inducing a laterally bent torso.

Increased angle of twist has been correlated with increased asymmetric muscle activation. Results from different research studies have concluded that the activation was high in the ES muscle contralateral to the direction of twisting (Marras and Mirka, 1992; Lavender et al., 1993; van Dieen, 1996). This imbalance of muscle forces between the right and left sides of the torso yields large shear forces acting at the lumbar spine (Lavender et al., 1989). There is an increase in compressive forces at the lumbar spine, as a result of the recruitment of individual trunk muscles that are necessary to stabilize the spine and resist an asymmetric load. Trunk muscle activation may be counterproductive to resisting the direct load, although maintaining trunk stability and posture was established (Lavender et al., 1992a).
As stated, the mechanism expected to cause asymmetric torque at the low back resulting in increased spinal loadings is a result of a need to stabilize the spine by co-contraction against the imposed perturbation. Plamondon, Gagnon and Gravel (1995) were not able to demonstrate lateral flexion or twisting torques significantly deviating from those torques recorded during similar symmetrical tasks. The authors proposed that twisting of the lower extremities evokes a pelvic twist to avoid lateral flexion and asymmetric loading. This biomechanical explanation would be insufficient in conditions of high degree of asymmetry. Kingma et al. (1998) also considered whether pelvic twist prevents asymmetric risk factors. The effects of asymmetric lifting ranging from 0 to 90 degrees was assessed under two conditions of lifting speeds and load magnitude and was analyzed with a 3D link segment model. Results indicated that lateral flexion and twisting torques were indeed associated with increasing lifting asymmetry. Pelvic twist was not used as an effective strategy to reduce asymmetric loading. Using an EMG based model, Marras and Mirka (1992) found increased co-activation of antagonistic trunk muscles with increasing task asymmetry. It may be concluded that even small deviations of a lifting movement from the sagittal plane may impose risk of LBP (Marras and Mirka, 1992; Granata and Marras, 1995).

Asymmetric or lateral perturbations also influence unique muscle recruitment patterns during anticipatory postural adjustments, as compared to similar symmetrical perturbations. Proximal muscle pairs are hypothesized to anticipate bilateral self-triggered perturbations; while the ankle synergistic muscles (TA-Sol) participate mainly in the compensation of lateral and rotational perturbations, especially during asymmetric movements (Aruin, Ota and Latash, 2001). It should be noted that these results
contradict the Winter, Prince, Frank, Powell and Zabjek (1996) model of balance in quiet stance predicting the role of the ankle muscles for anterior-posterior rather than medial-lateral direction as indicated by Aruin et al. (2001). In a more recent study Shiratori and Latash (2000), again confirmed that the distal ankle muscles were more responsive in compensating for asymmetrical perturbations. A range of actions associated with rotational and lateral perturbations were used to evaluate the separate effects of the perturbations on the trunk and lower extremity musculature. Directional-dependent asymmetries in APAs of the right and left distal ankle muscles have been quantified in response to a perturbation induced in the frontal (lateral) plane (Aruin et al., 2001).
Chapter 3

METHODOLOGY

Subjects

Seventeen healthy, female subjects volunteered for this study from the university population. Anthropometrics, expressed as means ± standard deviation, were as follows: 23.65 ± 2.37 years of age, 163.54 ± 6.4 cm tall, and 56.15 ± 7.0 kg in mass. Because the load applied in this study was standardized, the subjects’ average mass had to be within the range of 49 to 75 kg (Chaffin and Andersson, 1991). All participants were asked verbally about their current and recent state of low back health. Participants were not allowed to take part if they had any back injuries in the previous 5 years. Informed consent was obtained prior to participation in the study. The research was approved by the Graduate Committee of the Faculty of Human Kinetics. A copy of the information and consent form is included in Appendix A.

Experimental Design

This research study investigated the effects of load symmetry upon sudden loading to the hands, as it applies to trunk stability and whole-body control. Symmetrical loading was defined as the load that was imposed in the sagittal plane causing a forward flexion of the trunk. The condition of Asymmetrical loading referred to the load that was applied in the frontal/sagittal plane causing both forward flexion and a right lateral bend of the trunk (Figure 3). Asymmetrical loadings were always delivered to the
subject's right. For each condition the subject was asked to maintain upright posture while holding a box with arms extended comfortably. The participant was not able to see the box, which was placed behind a black curtain hanging down to the level of the participant's forearms. The perturbation was applied to the subject as a standardized step input, which induced a repeatable postural perturbation for each experimental condition and consecutive trial. Experimentally, the solid load weight was dropped into the hand held box from a constant height of 1 cm above the bottom of the box that the subject was holding at a comfortable arms reach.

The load magnitude used in this experiment was standardized relative to 25% of the average female lifting strength. The purpose of standardizing the load magnitude was to reduce variability in the study. As indicated, each subject must be within the average female mass range, referring to the 25th to 75th percentile, quantified from 49 to 75 kg (National Health Survey in Chaffin and Andersson (1991)). The load magnitude was determined from the average female arm and leg lifting strength data, as quantified by Chaffin, Herrin and Keyserling (1978). The average female arm lifting and torso lifting strengths are 200 N and 266 N, respectively. Thus, the average lifting strength, which is comparative to the muscular response required to respond to the hand-loading task in the current experiment, is 266 N. The load was scaled to 25% of the average lifting strength, for female subjects of an average mass of 62 kg. This % load was derived from pilot testing of loads of different magnitudes, which elicited neuromuscular responses that did not require a compensatory step. Thus, the load magnitude was standardized at 6 kg for all subjects.
A repeated measures design was used to assess Load Placement, both Symmetrical and Asymmetrical, in conjunction with the Timing variable, for each muscle pair recorded. The Timing condition was characterized by expected and unexpected loadings of the trunk. The subjects were always deprived of visual cues and were not able to visually determine what time the load would be applied. In the Expected condition, the subject was verbally cued as to when the weight would be dropped into the box (refer to Experimental Protocol). Again, there were no cues, verbal or visual, as to the time to load onset during the Unexpected condition.

The collection session consisted of 4 experimental conditions, each condition encompassed 10 trials with one-minute rest between conditions. The sequence of conditions was completely randomized, with the exception of the surprise condition, which was always the last trial of the final experimental condition (Marras et al., 1987).

The measured variables were the CoP displacement in the anterior-posterior (AP) and medial-lateral (ML) directions, as measured with the AMTI force plate, and the normalized surface electromyography (EMG) from the bilateral lumbar erector spinae (LES), thoracic erector spinae (TES), external oblique (ExO), internal oblique (InO), biceps femoris (BF), soleus (Sol) muscle pairs and the right tibialis anterior (TA) muscle.

Apparatus

A pipe work rod was hung from the ceiling to position pulleys directly above the hand held box. A steel cable ran through each pulley and attached to the load weight, which was dropped from a constant height of 1cm above the bottom of the box. This ensured that the sudden loading did not impose ballistic loading onto the spine. The load
weight was also padded with foam pieces at the point of contact with the bottom of the box to ensure that the perturbation induced a solid step input. Two pulleys aligned above the box, one for Symmetrical loading in the sagittal plane and the other for the frontal plane, Asymmetrical loadings (Figures 3 and 4). The distance between the Symmetrical and Asymmetrical load placements was 30 cm, while the moment arm from the lumbar spine to the load placement varied depending on the anthropometrics and posture adopted by each subject (van Dieen and deLooze, 1999).

![Diagram](image)

**Figure 3:** An overhead view of a subject holding the hand held box. Note the location of the symmetrical/asymmetrical loads and the moment arms as described above. Not to scale.

The subject was not be able to see the box, because of the black curtain hanging down to the level of the participant’s forearms (Figure 4). The box held by the subject was approximately 60 cm wide and divided into 3 compartments. It contained two
handles placed in the centre of the outer dimensions of the box, which enabled the subjects to hold it with a full palmer grip. During the symmetrical load placement the load weight was applied in the middle compartment and in the outer right compartment for the asymmetrical loading condition (Figure 3).

The load weight was made of a stack of 5 weight plates, each weighing 2 ½ lbs. forming a solid rigid mass. These were stacked and mounted onto a wooden platform that was suspended with a steel cable harness attaching to the pulley system.

Figure 4: Sagittal view of experimental apparatus with subject standing holding the box prior to sudden load onset. Co-ordinate system of the force plate shown. Not to scale.
Data Acquisition

Force Measures

The subjects stood at a preferred stance width on a biomechanical strain gauge force platform (Advanced Mechanical Technology Inc., AMTI; Newton Mass). The signals from the platform were amplified and used to measure reaction forces in three orthogonal directions (along the direction of gravity/vertical, $F_z$) and moments of forces in two directions (in the sagittal plane, $M_y$, and in the frontal plane, $M_x$). Data from the force plate was collected and converted by a 12-Bit A/D card (National Instruments) at a sampling frequency of 1000 Hz, using a PC compatible computer. The data was dual low-pass filtered with a second order Butterworth filter using a cut-off frequency of 10 Hz to remove any electronic noise present. The LabVIEW software (National Instruments) was used to process the displacements of the CoP. These displacements were calculated in the AP (CoP$_y$) and the ML (CoP$_x$) directions using the following calculations:

$$\text{CoP}_{ML} = \frac{M_y}{F_z}$$
$$\text{CoP}_{AP} = \frac{M_x}{F_z}$$

The CoP displacement was used to examine the existence, latency and amplitude parameters of the APAs. The AP and ML CoP excursions at load onset were assessed relative to the baseline CoP location recorded 150 msec prior to load onset (Aruin et al., 2001).
EMG Measures

The EMG activity of the following postural muscles were recorded bilaterally: LES, TES, ExO, InO, BF and Sol, with the exception of TA which was recorded from the right side only. If necessary, prior to the application of surface electrodes, the skin was shaved to remove excess hair and rubbed with alcohol to lower impedance. Pairs of Ag/AgCl surface electrodes (200 Medi-trace disposable electrodes, Graphic Controls) were attached after the skin preparation. The electrodes were positioned in the longitudinal direction above either the bulkiest part or the middle of the muscle belly with an intra-electrode distance of 2.5 cm. The electrode placement sites for the trunk musculature were the same as those described by McGill (1991) (Figure 5). The sites for the leg muscles are depicted in Figure 6. The EMG activity from the lower extremity muscles was recorded by similar methods as described by Jacobs and Ingen Schnau, (1992) and Aruin et al. (2001). To reduce movement artifacts in the EMG signal, the electrodes and connecting wires were carefully taped down over the muscle bellies. The EMG signals were amplified (1000 to 5000) prior to sampling, digitized with a 12-bit resolution at 1000 Hz and full wave rectified for further analysis. The same PC compatible computer, A/D converter and LabVIEW customized software were used to control the experiment, collect the data and perform most of the analyses.
Figure 5: Electrode locations and representative lines of actions for muscle monitored in this study. (A- posterior view, B- anterior view). TES: Thoracic Erector Spinae, LES: Lumbar Erector Spinae, EO: External Oblique, IO: Internal Oblique.
Figure 6: Lower extremity muscles monitored in this study. (A-posterior view, B-anterior view). BF: Biceps Femoris, Sol: Soleus, TA: Tibialis Anterior.

General Procedure and Experimental Protocol

Orientation

All subjects were brought in for an orientation session, on a separate day from the data collection session. This lasted approximately 15 minutes in duration. Subjects' anthropometric measures were recorded at this time. At this session subjects were
introduced to the sudden loading perturbation and allowed to familiarize themselves with the equipment and experimental set-up. The subjects were exposed to each of the Experimental conditions. The load conditions are described in further detail in the Data Collection section.

_Data Collection Session_

Initially the EMG electrodes were placed on the subject at the electrode placement sites as previously described and maximum voluntary contractions (MVCs) were performed (Figures 5 and 6).

The subjects were then instructed to stand upright on the strain gauge force platform. Subjects stood in a neutral upright posture, with feet separated at a preferred stance width, usually about shoulder width. Tape was then placed on the force plate to ensure consistent foot placement for each trial. Subjects were instructed to resist loading perturbations and attempt to maintain neutral posture relative to the vertical axis in the sagittal plane. Subjects were told to hold the box with arms extended comfortably in front of the body at waist height. The purpose of this described posture was that it was assumed to be similar to postures adopted when carrying a load for a distance. Following this, the pulleys were set and adjusted to the appropriate height and anthropometrics for each subject.

Once subjects were standing comfortably on the force plate the trigger for the data collection program was set according to each subjects’ anthropometrics. Subjects were asked to stand holding the box including the load weight while the program collected the signal for 7 seconds, followed by a second trial, in which the subject were asked to stand
in quiet stance with the hand held box only. The average voltage recorded for loaded and unloaded trials, measured from the vertical ground reaction force signal, was used as the trigger value for each subject. As the load was added in a given trial this mean vertical force was exceeded, setting off the trigger and initiating the data collection software. For each trial force and muscle activity data of the trunk and lower extremities were recorded for a total duration of 750 msec; 150 msec prior to the release of the load and for 600 msec after the trigger onset to ensure that the data log file fully depicted the recorded response to the load perturbation (Thomas et al., 1998).

Prior to any experimental conditions being performed, two seven second trials were recorded with subjects standing upright and still, one trial with eyes open and the other with eyes closed. These trials served simply to provide baseline measures of a subject’s balance (Wu and MacLeod, 2001).

**MVC Normalization Trials**

Following the application of the electrodes, the maximum voluntary contractions (MVC) were obtained for each of the individual muscles. MVC trials were used to normalize the recorded EMG signals to maximal activity. For each MVC, subjects were instructed to gradually ramp up their force to maximum and to avoid ballistic movements. Subjects were asked to hold the maximal contraction for a 2-3 second duration. Two MVC trials were collected for each muscle. For the LES, subjects were instructed to lie face down on the floor with their arms at their sides or behind their head and arch their back, with resistance being placed downward on the back of their legs. For the TES, subjects performed the same movement as for the LES while at the same time maximally contracting their shoulder blades together. For both the InO and ExO, subjects laid on
their backs with knees up with their feet held firmly in place. In this position subjects performed a sit-up with one shoulder to the opposite knee with resistance being placed on the moving shoulder for the InO and ExO MVCs. For the BF subjects stood while resting their hands on a table for balance and flexed their lower leg at the knee, against resistance. Subjects maximally contracted the Sol by standing on ball of their right foot and pushing upwards against resistance. For the TA, subjects stood on their right heel and lifted their front foot against resistance.

Approximately 30 seconds rest was provided between each exertion. The EMG signals were low-pass filtered using a 2nd order Butterworth filter. For each muscle the largest rectified and filtered (\( f_c = 3 \)Hz) voltage obtained in either of the two trials was denoted as maximal activation (MVC) for that muscle and was used to normalize EMG signals recorded in the collection session. All MVC trials were collected at 1000 Hz.

**Experimental Protocol**

Four experimental conditions were examined in this study. Throughout the entire experimental protocol subjects were instructed to look directly forward at all times and to try to maintain a state of equilibrium. In the first condition, the experimenter counted down from five to one and on one the load was released from its suspended position 1 cm above the bottom of the box, in the symmetrical (middle) compartment. This was termed the Symmetry x Expected condition. In the second condition, the experimenter verbally told the subject that the load would be applied in the symmetrical compartment but there would be no warning or knowledge of timing of any kind. This was termed the Symmetry x Unexpected condition. The following two conditions, termed Asymmetry x
Expected and Asymmetry x Unexpected, were similar to those described above other than the load was applied to the asymmetrical (outer) compartment of the hand held box. For the Expected timing conditions, approximately 10 seconds rest was given between trials; for the Unexpected timing condition rest ranged from 5 to 15 seconds between trials.

Ten trials were conducted for each condition, for a total of 40 trials in all. To reiterate, the four experimental conditions were randomized and then blocked. Dependent variables were calculated for each trial. For each subject the 10 trials for each condition were then averaged. These within subject means were then averaged across all subjects for each condition. See Figure 7 to view the ensemble averages of a condition that was averaged across all of the subjects.

A final surprise condition was examined and treated as an individual case study, separate from the statistical analysis. This condition involved both Symmetrical and Asymmetrical load placements for different subjects, in conjunction with unexpected timing of load onset, which was completely unexpected in nature. For all subjects this condition was presented last. No specific instructions were given to the subjects regarding their reactions for this trial. In this final trial the subjects anticipated a load onset similar to the trials from the previous experimental condition. In reality, the sudden loading will occur sooner than expected in the expected timing condition, at approximately 2 or 3 seconds. Due to the deceptive nature of this “surprise” trial, it was only presented once as the final trial of the experimental protocol. This ensured that the reaction and response to the Surprise condition, as compared to the Unexpected condition, would not affect the subjects’ response to the Experimental conditions.
Figure 7: Ensemble averages graphs recorded for the AP CoP during the Surprise condition (n = 14) and for the right Sol during the Asymmetry x Unexpected condition (n = 17). Activation expressed as % MVC EMG. The dark lines represent the average at each time.
Data Analysis

Trial Selection & Windowing

For each subject, ten trials for each condition were collected, dependent variables calculated and averaged. These within subject means were then averaged across all subjects within each condition. Trials were visually inspected for anomalous spikes or signals contaminated with ECG artifacts in the period around the load onset were discarded.

Force and EMG Data Treatment

Four dependent variables were examined for each measured signal: pre average, anticipatory adjustment, peak response, and time-to-peak response (Figure 8). The pre average was defined as the average level (% MVC or displacement) for the 15 ms prior to the load onset. The anticipatory adjustment was defined as the change from the baseline levels (% MVC for muscles; displacement for Centre of Pressure), averaged from 150 ms to 15 ms prior to the loading, to the pre-perturbation levels averaged over the last 15 ms prior to the load perturbation onset. This anticipatory change was calculated by the pre average minus the base average variables. The peak response to the perturbation was defined as the maximum change (increase) from the pre-perturbation level to the post-perturbation level. Peak response was derived from the peak amplitude response minus the pre average variable. The time-to-peak response was defined as the time from the onset of the perturbation to the maximum change post-perturbation.

The CoP displacement was the parameter used to verify the existence, latency and amplitude of APAs. Displacement of the AP CoP in the anterior direction was indicative
of anticipatory adjustments for the Symmetrical load placement, while the CoP
displacements in the ML direction reflected anticipation of the Asymmetrical
perturbation. An APA was determined when the AP or ML CoP deviates beyond 4 mm
on either side of the baseline sway (McIlroy and Maki, 1993a).

Raw EMG signals were low-pass filtered at a cut-off frequency of 3 Hz, full-wave
rectified and normalized to the maximum found for each muscle in the isometric MVC
trials. All signal treatments were completed digitally, post-collection, using LabVIEW
software. The onset of muscle activity was determined from the processed EMG signals
as the first data point where the rectified EMG clearly exceeds the baseline levels
(vanDieen and deLooze, 1999). More specifically, the onset latency was quantified as
the point when the EMG trace surpasses the quiet stance baseline EMG level by two
standard deviations for a duration of 25 msec or greater (Difabio, 1967).

Normalization of anticipatory EMG to background EMG is another method of
processing EMG signals. Integral measures of EMG data from the trunk and leg muscles
were used to characterize anticipatory EMG changes in the activity of the postural
muscles. Anticipatory muscle activity from 100 ms prior to the load onset to 50 ms after
the load was compared with baseline muscle activity measured during quiet stance. These
intervals are chosen based upon previous research that described APAs typically starting
about 100 to 150 ms prior to the focal movement. On the other hand, feedback effects
and reaction responses were not expected during the first 50 ms after perturbation onset
(Aruin and Latash, 1995a). Similar methods of comparing the preload area of normalized
EMG, which is a measure of the muscle activity prior to the onset of an impending load,
to muscle activity associated with the onset of the sudden load have been used in sudden
loading research (Thomas et al., 1998). Pre average EMG activity prior to the sudden load onset, anticipatory response (pre minus base average), peak EMG activity and time-to-peak latency were the dependent variables analyzed with this methodology.

Figure 8: Schematic representation of how data values for EMG will be derived from the collected traces. Average EMG activity prior to load onset will be calculated as the mean of the 100 – 50 ms prior to load onset. Trial values were taken as the peak of the respective curves.

Statistical Analysis

Again, the four dependent variables in this study are as follows: pre average, anticipatory response, peak response and time-to-peak response. These variables characterize the CoP and EMG data. A 3-way analysis of variance (ANOVA) with repeated measures was run on each of the dependent variables for each muscle pair, with
the exception of the TA, to determine if significant differences were evident between the 
Side (Right and Left), Load Placement (Symmetry and Asymmetry) and Timing 
(Expected and Unexpected) variables (Figure 9). In addition, a 2-way analysis of 
variance (ANOVA) with repeated measures was run on each of the dependent variables 
for the right TA muscle and as well as the two centre of pressure measures to determine if 
there were significant effects of Load Placement and Timing.

For significant interactions mean comparisons were used in the paired t-test post 
hoc test.

The surprise case study data for the bilateral muscle pairs recorded were assessed 
by a two-way analysis of variance (ANOVA) for each of the dependent variables. The 
within repeatable factor was Side, left and right side of each muscle pair, while the 
between factor was Load Placement. As for the TA muscle and the AP and MP CoP data 
was examined by one-way ANOVA with repeated measures for each of the dependent 
variables.

For all tests the significance level was set at least p < 0.05.
Figure 9: Schematic of the 2*2*2 repeated measures ANOVA model that was used for statistical analyses
Chapter 4

RESULTS

Due to the magnitude of the study (240 possible main and interaction effects) only those effects that were significant (approximately 20%) will be addressed. All main effects and interactions that will be reported are quantified and assessed as statistically significant at a level of at least $p < 0.05$. A summary of the statistically significant findings of the 3-way repeated measures ANOVA analysis for the EMG data and the findings for the 2-way repeated measures ANOVA for the CoP data are summarized in Table 1. Mean values can be found in Appendix B. The results of the overall test of significance revealed that the \textit{Load Placement x Timing} interaction was not statistically significant for any of the dependent variables measured and therefore will not be reported.

EMG

All terms in the ANOVA main effects [\textit{Side, Load Placement, Timing}] and the interactions [\textit{Side x Load Placement, Side x Timing}] showed significant $p$-values as indicated in Table 1. \textit{Post hoc} levels of significance will be referred to throughout the Results section, in conjunction with a table summarizing the t-test $p$-values (Table 3).
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Table 1: Summary of the significant main effects and interactions for the EMG data for the Side, Load Placement, and Timing independent variables, as determined by a 3-way ANOVA with Repeated Measures. Blank spaces indicate that no significance was found. Significance set at p < 0.05. Legend: * = p < 0.05, ** = p < 0.01, *** = p < 0.001, and **** = p < 0.0001, S = Bilateral Side, LP = Load Placement, T = Timing.
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<tr>
<td>TIMin</td>
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</tbody>
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Table 2: Summary of the significant main effects and interactions for the CoP Data for the Load Placement, and Timing independent variables, as determined by a 3-way ANOVA with Repeated Measures. Blank spaces indicate that no significance was found. Significance set at p < 0.05. Legend: * = p < 0.05, ** = p < 0.01, *** = p < 0.001, and **** = p < 0.001, LP = Load Placement and T = Timing.
<table>
<thead>
<tr>
<th>Muscle</th>
<th>Pre Average</th>
<th>Pre - Base (Anticipatory Response)</th>
<th>Peak - Pre (Peak Response)</th>
<th>TTPk (Time-to-Peak Response)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES</td>
<td>S x L</td>
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<td>L Asym &lt; R Asym</td>
<td>S x L</td>
</tr>
<tr>
<td>LES</td>
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<td>L Asym &gt; R Asym</td>
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</tr>
<tr>
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<td>S x L</td>
<td>NS</td>
<td>L Unexp &gt; R Unexp</td>
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<td>S x L</td>
<td>NS</td>
<td>R Asym &gt; L Asym</td>
<td>S x T</td>
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<tr>
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<td>R Asym &gt; L Asym</td>
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<tr>
<td>Sol</td>
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<td>L Sym &gt; R Sym</td>
<td>R Asym &gt; L Asym</td>
<td>S x L</td>
</tr>
</tbody>
</table>

**Table 3:** Summary of post hoc findings from analyses of Side (S) x Load Placement (L) and Side (S) x Timing (T) interactions for conditions determined significant by the ANOVA results. Significance set at p < 0.05. Legend: S – Side, L– Load Placement, T– Timing, Exp – Expected, Unexp– Unexpected, Sym – Symmetry, and Asym – Asymmetry.
Pre Average

The pre average variable was defined as the average EMG %MVC or CoP position for the 15 ms prior to added load perturbation. The average AP CoP position prior to the loading perturbation yielded a main effect of Timing ($p < 0.05$). For the Expected timing condition, the AP CoP was displaced 5% more anteriorly than the CoP position observed in the Unexpected timing condition.

The average ML CoP position prior to the load onset showed a significant main effect of Load Placement ($p < 0.001$). Prior to the Symmetrical load condition, the ML CoP showed a displacement that was 60% more medial (towards the left side) than the Asymmetrical condition, which was displaced laterally (towards the right side). Figure 10 charts the ML CoP pre average position.

![ML CoP: Pre Average](image)

Figure 10: The main effect of Load Placement for the ML CoP pre average variable. Standard error bars are indicated. Significance set at $p < 0.05$. ($n = 34$).
Trunk Extensors

With regards to pre average muscle activation, both of the posterior trunk muscles, the TES (p < 0.01) and LES (p < 0.01), exhibited a similar main effect of Timing. There was a 10% increase in muscle activity for the TES and 6% for the LES in the Expected condition when compared to the Unexpected timing condition (Figure 11). Although the Timing main effect evoked increased activation levels that were significant for the reported results, the absolute magnitude of the increase in the TES and LES activity levels (% MVC) was marginal.

![Graph showing EMG: Pre Average (Main Effect: Timing)]

Figure 11: The main effect of Timing for the pre average muscle activation levels for TES and LES muscle pairs. Activation expressed as pre average %MVC EMG. Standard error bars are indicated. Significance set at p < 0.05 for both muscles. (n = 68).
The ANOVA results for the pre average variable also revealed a *Side x Load Placement* interaction for the trunk extensors, TES (\(p < 0.05\)) and LES (\(p < 0.0001\)). The interaction for the TES muscle pair showed 6% more activation on the right side compared to the left side, under only Asymmetrical loading conditions. In comparison, the LES muscle pair showed 25% more activation for the left side compared to the right side under only Asymmetrical loading condition (Figure 12).

**Trunk Flexors**

The trunk flexors (ExO; \(p < 0.05\) and InO; \(p < 0.05\)), both revealed a *Side x Load Placement* interaction. However, the absolute magnitude (% MVC) of the differences between the right and left sides, for both flexors was minimal (Appendix B: Table 6).

**Leg Muscles**

The pre average variable of the Sol leg muscle was also observed to have a significant *Side x Load Placement* interaction. Similar to the oblique muscles, the absolute magnitude of the difference between the right and left side mean activations (%MVC) was not functionally relevant (Appendix B: Table 6).
Figure 12: Side x Load Placement interaction plot for the pre average variable for the left and right TES and LES muscle pairs. Activation expressed as pre average % MVC EMG. Significance set at p < 0.05. (n = 34 experimental data; n = 5 surprise asymmetry; n = 9 surprise symmetry). * - denotes significance.
The Surprise case study data generally showed similar trends to the experimental data, for the pre average variable. There were no significant effects found for Side or Load Placement in the Surprise condition. However, the activation level (%MVC) for the pre average response was higher for the TES (Figure 12). The right side of the TES was found to be more activated than the left side in the Asymmetrical Surprise condition when compared to the Experimental conditions. Under the Symmetric loading condition, the left side was more activated than the right side for the Surprise, which contrasted the experimental conditions where there were no bilateral differences for the Symmetrical conditions.

**Anticipatory Response**

Anticipatory adjustment was defined as the change observed from the baseline levels (% MVC for muscles; displacement for Centre of Pressure), averaged from 150 ms to 15 ms prior to the loading, to the pre-perturbation levels averaged over the last 15 ms prior to the loading perturbation. The displacement of the AP and ML CoPs provided a window of the whole-body anticipatory adjustments. A significant *Timing* main effect (p < 0.01) was observed for the AP CoP. In the Expected condition, the anticipatory response was significantly greater than in the Unexpected timing condition (Figure 13). It is to be noted that the magnitude of this displacement was only 0.25 cm and has questionable functional relevance. The ML CoP displacement did not reveal any significant differences in preparation of the load onset.
Figure 13: The main effect of Timing in the AP CoP anticipatory response variable. Standard error bars are indicated. Significance set at $p < 0.05$.

Trunk Extensors

Of the trunk extensors, the LES (by 38%, $p < 0.001$) showed a main effect of Timing, in which there was pattern of the Expected condition having a larger anticipatory response than the Unexpected conditions (Figure 14).

The ANOVA results for anticipatory variables also revealed a Side $\times$ Timing interaction for TES ($p < 0.05$). For the TES muscle pair, it was found that the right side was activated more than the left side in the Expected timing condition, while there was a minimal bilateral difference between the right and left side for the Unexpected condition.
Figure 14: The main effect of Timing for the anticipatory response for the LES and BF muscle pairs. Activation expressed as pre average minus base average in %MVC EMG. Standard error bars are indicated. Significance set at $p < 0.05$ for each muscle. ($n = 68$).

The Side x Load Placement interaction was prevalent for the anticipatory response variable, and was identified for LES ($p < 0.0001$). This interaction can be viewed in Figure 15. The LES showed a dramatic difference of 90% higher activation for the left side as compared to the right side under Asymmetrical conditions ($p < 0.0001$), while Symmetrical conditions evoked little bilateral difference (Appendix B: Table 6).
Figure 15: *Side x Load Placement* interaction plots for the anticipatory response for the left and right LES and InO muscle pairs. Activation expressed as the pre average minus the base average in % MVC EMG. Significance set at $p < 0.05$ for each muscle. (n = 34). * - denotes significance.
Trunk Flexors

The ANOVA results for the anticipatory variable also revealed a Side x Timing interaction for ExO (p < 0.05) and InO (p < 0.05). Similar to the pattern noted for TES, the InO muscle pairs exhibited higher activation for the right side than the left side in the Expected timing condition, while there was a minimal bilateral difference between the right and left side for the Unexpected condition (Figure 16). The right side ExO anticipatory response was 30% higher in the Expected condition relative to the Unexpected timing condition. It was also observed that the left side of the ExO muscle pair was more activated than the right side for both the Expected and Unexpected timing conditions.

The InO (p < 0.01) also showed a significant Side x Load Placement interaction for the anticipatory response variable (Figure 15) with a 40% increase in the right side over the left side activation levels under Asymmetrical conditions.
**Figure 16:** *Side x Timing* interaction plots for the anticipatory response variable for the left and right InO and ExO muscle pairs. Activation expressed as the pre average minus the base average in % MVC EMG. Significance set at $p < 0.05$ for each muscle. ($n = 34$). * - denotes significance.
**Leg Muscles**

The BF (p < 0.001) elicited a 34% higher anticipatory response for the Expected timing condition relative to the Unexpected condition (Figure 14).

The *Side x Load Placement* interaction was found to be significant for both the BF (p < 0.05) and Sol (p < 0.0001) leg muscles. Each of the lower extremity muscle pairs recorded (BF; p < 0.01 and Sol; p < 0.01), exhibited significantly higher activation levels for the right side than the left under Asymmetrical conditions. Similar to the LES and InO muscle pairs, the BF did not reveal a large difference between sides under the Symmetrical load placement condition. However, the Symmetrical condition did produce higher activation levels for the left side versus the right side of the Sol muscle pair (p < 0.05). The activation level (% MVC) of the left Sol muscle was higher under the Symmetrical loading, relative to the Asymmetric condition (Figure 17).
Figure 17: Side x Load Placement interaction for the BF and Sol muscle pairs. Activation expressed as pre average minus base average in % MVC EMG. Significance set at p< 0.05 for each muscle. (n = 34). * - denotes significance.
Relative to the experimental conditions there were different trends of activation observed during the Surprise condition. For the TES and InO, bilateral differences were exhibited in the Symmetrical loading condition for the Surprise trial, while the right and left sides equally anticipated the load onset during the Experimental conditions. The right side was activated more than the left side for the TES (Figure 18) and the left side more than the right for the InO muscle pairs for Surprise Symmetrical condition. For the TES, the left side showed more change than the right side under Asymmetrical loading during the Surprise condition, which was contrary to the experimental condition in which the right side was more activated than the left side under Asymmetrical loading (Figure 18). For the InO, the Asymmetrical load placement evoked the same trend of activation, the right side more than the left side, in both the experimental and Surprise conditions.

Similar anticipatory activation of the BF, Sol and TA leg muscles were evoked under Symmetrical loading in the Surprise and Experimental conditions. For the BF, the bilateral difference was smaller for the Surprise condition as opposed to the Asymmetric experimental condition. The Sol muscle pair evoked co-contraction of the right and left side for the Asymmetrical load placement during the Surprise condition, differing from the bilateral differences evoked in the Experimental condition.
Figure 18: *Side x Load Placement* interaction plots for the anticipatory response during the Surprise Condition for the TES muscle pair. Activation expressed as the pre average minus the base average in % MVC EMG. Significance set at p < 0.05 for the muscle. (n = 34 experimental data; n = 5 surprise asymmetry; n = 9 surprise symmetry).

**Peak Response**

The peak response to the perturbation was defined as the maximum change from the pre-perturbation level to the post-perturbation level. As indicated, for each experimental condition, ten consecutive trials were conducted and averaged for each subject, and then averaged across all subjects for each condition. See Figures 19 and 20 to view the ensemble averages of the averages of four different experimental conditions, for four unique dependent variables.
Figure 19: Compensatory response ensemble graphs for the AP and ML CoP variables. The data was averaged for all 17 subjects and across all four experimental conditions. Displacement expressed as cm. (n = 68). The data was averaged for all 17 subjects and across all four experimental conditions. Displacement expressed in cm. (n = 68).
Figure 20: Compensatory response ensemble graphs for the left LES and right Sol muscles. The data was averaged for all 17 subjects and across all four experimental conditions. Activation expressed as % MVC. (n = 68).
The peak response for the AP CoP exhibited a significant main effect of Timing ($p < 0.0001$). Figure 21 depicts a 20% larger anterior displacement produced under Unexpected versus Expected loading conditions.

![AP CoP: Peak Response](image)

**Figure 21:** The main effect of *Timing* in the AP CoP peak response. Standard error bars are indicated. Significance set at $p < 0.05$ for each muscle. ($n = 34$).

The peak response for the ML CoP exhibited significant main effects for both *Load Placement* ($p < 0.0001$) and *Timing* ($p < 0.05$). The average peak (minimum) displacement for the ML CoP was a negative value, indicating a lateral displacement (to the right side). For asymmetrical loading conditions, the ML CoP evoked greater lateral displacement towards the right side, as compared to the Symmetrical condition (Figure 22). With regards to *Timing*, there was a 8% increase in the peak lateral response to the Unexpected, as compared the Expected timing, conditions.
Figure 22: The main effect of Load Placement for the ML CoP peak response variable. Standard error bars are indicated. Significance set at $p < 0.05$. ($n = 34$).

There was a significant main effect of Timing for all of the muscles recorded, with the exception of TES. LES ($p < 0.001$), ExO ($p < 0.01$), InO ($p < 0.05$), BF ($p < 0.001$), Sol ($p < 0.0001$) and TA ($p < 0.001$) all exhibited higher muscle activity levels with Unexpected timing. The largest relative increase in activation was found in the Sol muscle pair with a 24% higher muscle activity level in the Unexpected condition. Figure 23 illustrates the main effect of Timing on all the muscle pairs indicated above. It is worth noting that this figure also provides an overview of the relative activation levels between all of the muscles recorded for the peak response.
Figure 23: The main effect of Timing for the peak response variable for TES, LES, ExO, InO, BF, Sol and TA muscle pairs. Activation expressed as the peak average minus pre average in %MVC EMG. Standard error bars are indicated. Significance set at $p < 0.05$ for all of the muscle pairs. * - denotes significance. (n = 68 for the all the muscles except TA; n = 34 for TA).

Trunk Extensors

Each of the posterior trunk muscles exhibited a significant interaction in peak response between Side and Load Placement. For the TES, the peak response of the right side was 25% higher, than the left side in the Asymmetrical loading condition ($p < 0.05$) (Figure 24). To the contrary, the LES (by 70%, $p < 0.0001$) muscle pair showed higher activation levels for the left side relative to the right side during Asymmetrical loading (Figure 26). There were no bilateral differences observed for either muscle under Symmetrical loading.
Figure 24: *Side x Load Placement* interaction plots for the peak response during the Surprise condition for the TES muscle pair. Activation expressed as the peak average minus pre average in %MVC EMG. Significance set at $p < 0.05$ for the muscle. ($n = 34$ experimental data; $n = 5$ surprise asymmetry; $n = 9$ surprise symmetry). * - denotes significance.

**Trunk Flexors**

The InO did reveal a *Side x Timing* interaction ($p < 0.05$) in the ANOVA results, although *post hoc* analysis of this interaction did not yield any statistical significance.

Similar to the LES, the ExO ($p < 0.01$) elicited a significant interaction in peak response between *Side* and *Load Placement*. The ExO showed a 40% higher activation for the left side relative to the right side during Asymmetrical loading. There were no bilateral differences observed for the right and left ExO under Symmetrical loading.
Leg Muscles

The load symmetry variable evoked a significant main effect of Load Placement for the TA (p < 0.05). Muscle activation in the Asymmetrical loading conditions was 18% higher than the Symmetrical condition for the TA (Figure 25).

Figure 25: The main effect of Load Placement for the peak response variable for TA muscle pair. Activation expressed as the peak average minus pre average in %MVC EMG. Standard error bars are indicated. Significance set at p < 0.05 for the muscle. (n = 34).

The leg muscle pairs of BF (p < 0.0001) and Soleus (p < .0001) also demonstrated a significant Side x Load Placement interaction. For both the Sol and BF muscles groups, the right side activation levels were higher in Asymmetrical loading than the left side (Figure 26).
Figure 26: *Side x Load Placement* interaction plots for the peak response for the LES and BF muscle pairs and the peak response for the LES during the surprise condition. Activation expressed as the peak average minus pre average in %MVC EMG. Significance set at p < 0.05 for all of the muscle pairs. (n = 34 experimental data; n = 5 surprise asymmetry; n = 9 surprise symmetry). * - denotes significance.
In the Surprise case study the load was presented both symmetrically and asymmetrically in a completely unpredictable fashion, as subjects were deceived into thinking that had knowledge of the temporal load onset. Under the Symmetrical load placement the AP CoP was displaced, on average, 1 cm more in the anterior direction during the Surprise condition, as compared to the peak response in the experimental condition. To the contrary, the peak response for the ML CoP was equally displaced in the medial direction for the surprise and experimental conditions.

The peak response for the LES and InO muscle pairs were found to exhibit a main effect of Side during the Surprise condition. The LES (By 36%, p < 0.05) and InO (By 24%, p < 0.05) were activated more on the left side than the right side. The peak response of the LES also revealed a significant Side x Load Placement interaction. This interaction mirrored the same pattern of bilateral differences and load placement effects that characterized the Side x Load Placement interaction in the experimental conditions but at a slightly higher magnitude of response (Figure 26).

The TES did not reveal any statistical significance in the Surprise data, while the activation pattern showed patterns that differed from the experimental condition. Under the Asymmetrical condition the left side was more activated than the right side, which differs from the bilateral asymmetry evoked in the experimental condition. Symmetrical loading in the experimental condition revealed an equally activated response from both the right and left sides, while the Surprise condition evoked asymmetries between the right and left sides (Figure 24).

The InO was not found to have a significant Side x Load Placement interaction in either the surprise or experimental conditions, yet the pattern of activation was unique for
the two conditions. Figure 27 illustrates the asymmetries of the activation patterns of the InO muscle group in the surprise versus the experimental condition for the InO.

**Figure 27:** *Side x Load Placement* interaction plots for the peak response during the Surprise condition for the InO muscle pair. Activation expressed as the peak average minus pre average in %MVC EMG. Significance set at $p < 0.05$ for the muscle. ($n = 34$ experimental data; $n = 5$ surprise asymmetry; $n = 9$ surprise symmetry).

There were no significant effects to report for the leg muscles during the Surprise condition. Overall, all of the leg muscles recorded showed a higher peak response during the Surprise condition as compared to the experimental condition. The Sol was the only leg muscle to respond with an altered activation pattern in the Surprise condition. Under symmetrical loading the left Sol was found to be more activated than the right side for both experimental and surprise conditions. However, the asymmetrical loading differed
in that the left and right sides were activated equally for the Surprise condition, while the experimental condition showed bilateral differences (see Figure 28).

**Figure 28:** *Side x Load Placement* interaction plots for the peak response during the Surprise Condition for the Sol muscle pair. Activation expressed as the peak average minus pre average in %MVC EMG. Significance set at *p* < 0.05 for the muscle. (n = 34 experimental data; n = 5 surprise asymmetry; n = 9 surprise symmetry).
Time-to-Peak Response

The time-to-peak response variables for both the AP and ML CoP did not reveal any significant effects.

Trunk Extensors

A significant interaction was found between Side x Load Placement for TES (p < 0.05) and LES (p < 0.001) posterior trunk muscles (Figure 30). Both trunk muscle pairs elicited lower time-to-peak for the left side than the right side for the Asymmetrical conditions, relative to the Symmetrical loading condition that did not reveal significant bilateral differences.

Trunk Flexors

A significant Side x Timing interaction was found for the InO (p < 0.05). The difference was found in the activation of the left side, which had a 10% lower time-to-peak, relative to the right side, in the Unexpected versus the Expected condition (Figure 29).
Figure 29: Side x Timing interaction plot for the time-to-peak for the InO muscle pair. Activation represented by change in %MVC. The EMG latency expressed as the time-to-peak in msec. Significance set at $p < 0.05$ for all of the muscle pairs.

Similar to the LES, the ExO ($p < 0.001$) also revealed a significant Side x Load Placement interaction. This trunk flexor showed a pattern of the left side having lower times-to-peak than the right side under Asymmetrical loading conditions; whereas the Symmetrical condition evoked a marginally less time-to-peak for the left side as compared to the right side (Figure 30).
Figure 30: *Side x Load Placement* interaction plots for the time-to-peak variable for the TES and ExO muscle pairs. Significance set at $p < 0.05$ for all of the muscle pairs. * - denotes significance.
Leg Muscles

There was a significant effect of Timing for the Sol (p < 0.05) (Figure 31) with a lower time-to-peak in the Unexpected condition relative to the Expected timing condition (10% faster). In the Expected timing condition, both muscles reached their relative peak response at about the same time. In contrast, in the Unexpected condition the Sol had a lower time-to-peak response while the TA has a higher time-to-peak (Figure 31) (Appendix B: Table 5).

![Soleus and TA: Time-to-Peak Response](image)

**Figure 31:** The main effect of Timing in the time-to-peak variable for the Sol and TA muscles. The EMG latency expressed as the time-to-peak- in msec. Standard error bars are indicated. * - denotes significance. Significance set at p < 0.05 for both muscles. (n = 68 for Sol, n = 34 for TA).

The BF (p < 0.05) was the only leg muscle, which exhibited a significant Side x Load Placement interaction, as under the Asymmetrical loading the right side elicited a
lower time-to-peak response than the left side. The bilateral differences between the left and right sides were significant in the Asymmetrical loading condition only (Figure 32) (Appendix B: Table 6).

![Graph showing EMG latency for BF muscle](image)

**Figure 32:** *Side x Load Placement* interaction plots for the time-to-peak variable and the surprise time-to-peak response for the BF muscle. The EMG latency expressed as the time-to-peak in msec. Significance set at $p < 0.05$ for all of the muscle pairs. ($n = 34$, $n = 9$ for surprise symmetry (BF), $n = 5$ for surprise asymmetry (BF). * - denotes significance.

There were no significant results found for the AP and ML CoP for the Surprise condition. However, the trends were similar to those found in the experimental condition for the AP CoP, although the Surprise condition evoked a lower time-to-peak for the Asymmetrical loading condition and a higher time-to-peak for the Symmetrical loading condition.
Again there were no significant differences found for the *Side* or *Load Placement* effects. For the TES trunk muscle pair the time-to-peak response was consistently lower under Asymmetrical loading in the Surprise condition, as compared to the experimental. To the contrary, the ExO was found to have a higher time-to-peak under Asymmetrical loading in the Surprise condition, while the experimental condition revealed lower time-to-peak for the left side under the Asymmetrical load placement.

A significant *Side x Load Placement* interaction was found for the BF (p < 0.05) (see Figure 32). The BF exhibited a lower time-to-peak for the right side than the left side under Asymmetrical loading concurring with the experimental condition. The Surprise condition did achieve the times-to-peak unique from those of the experimental condition. The temporal recruitment pattern differed for the Surprise condition in that the BF was activated prior to Sol or TA.
Chapter 5

DISCUSSION

This study extends previous findings on anticipatory responses prior to a sudden load onset, for both the trunk and leg muscles, and the control of whole-body equilibrium and trunk stability in the event of sudden loading to the hands. To investigate the extent of the relationship between whole-body postural control and trunk stability, the affects of load timing and load symmetry were used to challenge biomechanical equilibrium. Anticipatory and compensatory postural adjustments were evoked by the CNS to regulate both whole-body and trunk stability.

Common principles were found to facilitate the control of stability. The anticipation of load onset reduced the kinematic displacement of the body CoM and overall postural disturbance prior to load onset. Preparatory and compensatory strategies elicited bilaterally symmetrical activation and co-contraction recruitment patterns to increase muscle stiffness and overall stability. AP and ML stability were maintained through directionally specific activation patterns of agonistic and stabilizing trunk and leg muscles. Stereotypically coordinated temporal recruitment patterns were evoked to regain postural and trunk stability.

All of these principles were observed to govern the control of trunk stability and whole-body equilibrium. Although trunk stability and postural control are regulated by similar mechanisms, the control of each is functionally independent, and yet in parallel to one another. In the event that postural equilibrium was highly compromised, such as in
the Surprise condition, the control of whole-body equilibrium became a priority over trunk stability. Thus, it may be inferred that trunk stability and whole-body posture are not mutually exclusive.

Limitations

There are several limitations that should be addressed with regards to this study, prior to re-addressing the hypotheses.

Sample Size

The subject pool for this study was restricted to a female gender and university-aged demographic. Caution must be exercised upon making inferences based on the interpretation of data from any small sub-sample population. The prevalence of within subject variability, especially in relation to the range of peak muscular responses observed, creates difficulty when attempting to apply the data to another subject population.

Influence of Predictability and Habituation

It was a concern that the data collection involved 40 sequential, sudden hand-loading trials; that subjects would become habituated and demonstrate learned responses, which may confound the data. Lavender et al. (1993) reported that repeated exposures to a similar perturbation result in the subjects eliciting reduced peak muscular response and
a decrease in the overall postural disturbance. Thus, diminishing the impact of the step input perturbation.

The experimental conditions were randomized for each subject in an attempt to decrease habituation to the sudden loading and decrease predictability of the Unexpected timing condition. However, it was still possible that subjects were able to prior plan and minimize the destabilizing effect of the perturbation, by increasing co-contraction prior to load onset. Despite these efforts, it was unlikely that predictability had an effect on the response since the results of the Surprise condition, the only true window of the effects of an unanticipated, sudden perturbation, evoked similar recruitment and activation patterns to the Unexpected experimental conditions. In addition, subjects were unaware of the exact time-to-load onset in the Unexpected timing conditions. All of the muscles observed in this study, with the exception of the TES, exhibited higher amplitude EMG signals with Unexpected timing (Figure 23). Therefore, regardless of the ability to preplan and its possible effect on preparatory and compensatory strategies to regain trunk and whole-body stability, it doesn’t appear as though preplanning would alter the interpretations of the present study.

*Load Symmetry*

In this study the load was applied to the hands, away from the body, for both load symmetry placements. Asymmetrical loadings were always delivered to the subject’s right. An assumption was made that Asymmetrical loadings that are applied on the left would generate a mirrored response to that seen in the current study. Many other studies made the similar assumptions although methods of application differed (Lavender *et al.*, 92
Another consideration was the use of right-hand dominant subjects, in combination with Asymmetric load placement that delivered the perturbation to the right side. The choice to restrict to subjects with right hand dominance only was to simplify the complexity and dimensions of the study. Yet it is questionable to what extent lateral dominance would play a role in the proficiency of elicited anticipatory and compensatory strategies. Demura, Yamaji, Goshi and Nagasawa (2001) examined the effect of lateral dominance of legs on recruitment and muscle activation patterns. The dominant leg tended to perform better than the non-dominant during functional motor tasks. However, lateral dominance was not found to be remarkable for short-term latency movements, such as the APAs and reactive postural responses elicited in the current study. Therefore lateralization would have a marginal influences on the CNS mechanisms adopted to regulate trunk stability and postural equilibrium. Due to the muscle onset latencies and times-to-peak recorded in this study, ranging from 90 to 250 msec following load onset, the impact of right-hand dominance is assumed to be negligible.
Hypotheses

1. In the Asymmetrical loading condition, the left LES, TES and ExO agonistic trunk muscles, will respond with higher activation. The right side InO and ExO, which are antagonistic, stabilizing muscles of the trunk, will exhibit a higher peak muscle activity, relative to the Symmetrical loading conditions. Under Asymmetric conditions the time to peak onset latency will be longer versus the onset latencies in Symmetrical loading.

It was proposed that trunk muscles on the left side would be required to generate an increased agonistic activity to counter the lateral bend imposed by the Asymmetric load (Lavender et al., 1992a; Lavender et al., 1995). Thomas et al. (1998) also found that antagonistic trunk muscles were activated to maintain upright posture and trunk stability in response to an asymmetric perturbation.

The peak response of the left LES and ExO was found to be higher than the right side under Asymmetric loading (Figure 26). However, the right TES was more activated than the left side in response to the Asymmetrical load placement (Figure 24). Meanwhile the InO did not evoke asymmetries between the right and left sides for either Symmetrical or Asymmetrical conditions, as predicted (Figure 27). Therefore, the hypothesis may not be accepted as the results found that recruitment of the left LES and ExO responded as lateral agonists to resist the load perturbation, while the right TES muscle was activated to stabilize the trunk in the Asymmetrical condition.

Asymmetric loading conditions were predicted to evoke complex muscle recruitment patterns that increased time-to-peak onset latencies. To the contrary, in response to Asymmetric loading the TES, LES and ExO muscles were found to have lower times-to-peak for the left, agonistic side (Figure 30). Therefore the hypothesis was
not accepted and it may be concluded that the increased peak response of the lateral agonists were imperative to trunk stability for the Asymmetric loading perturbation.

2. *During Asymmetrical loading, the leg muscles will respond with an increase in the muscle activity of BF and Sol on the right side of the body, relative to muscle recruitment patterns in Symmetrical loading.*

An increase in the activation of the right side lower extremity muscles was assumed to resist the laterally induced moment applied in the Asymmetrical condition (Horak and MacPherson, 1997). It was assumed that the increased activity of the ipsilateral lower leg muscles enables the body to resist and counteract the Asymmetric perturbation by changing the shear forces acting at the support surface. Thus, exerting force against the surface shifts the CoM more medially towards its original position within the BoS, regaining lateral stability (Henry, Fung and Horak, 1998; Reidtyk, Patla, Winter, Ishac and Little, 1999).

The BF and Sol muscles pairs both responded with higher peaks on the right side versus the left side for the Asymmetric loading condition (Figures 26 and 28). Anticipatory adjustments also evoked greater change for the right as compared to the left side for the BF and Sol (Figure 16). Thus the results support the proposed rationale; thereby, the hypothesis is accepted.

3. *Peak muscle co-activation levels, in response to the sudden, Unexpected perturbation, will be higher than those evoked in the Expected condition.*
Marras *et al.* (1987) found that sudden, unexpected perturbations produced greater peak muscle responses of the agonist and antagonist trunk muscles, than those perturbations with known timing.

Each of the muscles sampled from both the trunk and lower extremities elicited higher peak responses in the Unexpected timing condition, relative to the Expected timing condition (Figure 23). The main effect of *Timing* found for all muscles recorded supported the hypothesis.

The hypothesis was validated further as the TES, LES, ExO, InO, BF and Sol muscle pairs all responded with bilaterally symmetrical activation of the right and left sides during Symmetrical loading (Figures 24 and 26).

4. *In the Unexpected loading condition, there will be a shorter time-to-peak latency for both the agonist/antagonist trunk and lower extremity muscles, compared to the Expected timing condition.*

Marras *et al.* (1987) and Thomas *et al.* (1998) both observed greater rates of onset of the agonist and antagonist trunk muscles for the sudden, unexpected perturbation, relative to a perturbation where the time-to-load onset was known.

Expectancy of load onset did not affect the times-to-peak for agonist and antagonist muscles acting to regain trunk stability following the perturbation. The InO was the only muscle for which the timing variable significantly differentiated the time-to-peak response. During the Unexpected timing condition, the InO responded with a shorter time-to-peak latency, as compared to the Expected timing condition (Figure 29).
A main effect of *timing* was found for the Sol and TA muscles for the time-to-peak variable. However, while the Sol showed a lower time-to-peak, the TA responded with a higher time-to-peak under the Unexpected loading condition (Figure 31).

Therefore, based on these results, the hypothesis may not be accepted.

5. *The APAs will be smaller in the Unexpected condition when compared to the Expected condition.*

*Lavender et al.* (1993) showed that the overall postural disturbance was not reduced in the unexpected loading condition. It was assumed that there would be insufficient warning time to generate an APA prior to load onset, in the Unexpected condition. In the current study, APAs are reflected in the displacement of the CoP prior to load onset.

In the Expected timing condition the AP CoP evoked an anticipatory shift in the forward direction that was 0.25 cm more in the anterior direction than the APA evoked in the Unexpected timing condition (Figure 13). Although the result of the AP APA was statistically significant, caution must exercised with regards to the interpretation of its functional relevance, given that the mean absolute displacement was 0.25 cm. There was not a significant APA evoked in the ML direction, as the ML CoP did not show a significant displacement with regards to the *timing* variable.

Thus, the findings support the hypothesis that anterior-posterior APA adjustments prior to the anticipated load perturbation, regardless of load symmetry, changed significantly more than the APAs evoked prior to the Unexpected timing condition.
6. *In the Expected loading condition, the APA will be increased in the M-L direction under Asymmetrical versus Symmetrical loading. This effect will not be observed in the Unexpected condition.*

In anticipation of the lateral component of the Asymmetric perturbation, it was hypothesized that the CoP would shift in the M-L direction to compensate for the expected load onset but not for the unexpected timing condition (Wu and MacLeod, 2001).

The results of the ML CoP did not reveal any significant differences in anticipation for the load onset. However, the average ML CoP displacement of the subject prior to Symmetrical loading was positioned more medial relative to the laterally adopted position prior to the Asymmetrical condition (Figure 10).

Although the trend indicates that the ML CoP anticipates load symmetry, the hypothesis cannot be accepted due to the lack of a significant *timing* effect or interaction between *Load Placement* and *Timing* variables.

7. *The hypothesized differences between the Expected and Unexpected conditions will be more pronounced in Asymmetrical loading conditions.*

Asymmetrical loading conditions are considered to evoke a more destabilizing perturbation, relative to symmetrical loadings (Lavender *et al.*, 1992a; Kingma *et al.*, 1998; Thomas *et al.*, 1998). Wu and MacLeod (2001) have shown increased lateral instability under Asymmetric conditions. It was assumed lateral instability evoked in the Asymmetrical conditions would be magnified under sudden, unexpected loading.

The results revealed that the *Load Placement* x *Timing* variables did not significantly interact for any of the dependent variables and muscles sampled. Although
main effects of Load Placement and Timing were observed, the hypothesis cannot be accepted without evidence of significant interactions and subsequent compounding of affects of significant interactions between these variables.

Main Findings

Whole-Body Postural Control

The control of the body CoM is an inherent requirement for the regulation of postural equilibrium. It is widely accepted that the CoM must be positioned within the BoS during bilateral stance to maintain balance (McIlroy and Maki, 1993b; Winter, 1995). Muscle activation and recruitment, primarily of the lower extremities, serves to control the movement of the CoP in the appropriate direction, which in turn facilitates the stability of the CoM position and maintains upright posture (Horak and Nashner, 1986; Horak and MacPherson, 1997). The current research results concur with other postural literature (Toussaint et al., 1997; Winter, 1995) that control of the CoP serves a crucial role in maintaining whole-body biomechanical equilibrium. Equilibrium is ensured by keeping the CoP movements larger and anterior of the body CoM displacements. Thus, CoP movement provides a window to understanding whole-body stability.
Anticipatory Response

In anticipation of the externally applied perturbation, a number of mechanisms serve to maintain the equilibrium. Among these preparatory strategies are changes in the resting activity of postural muscles prior to the perturbation. The anticipatory response observed in the monitored leg muscles was intended to counteract the destabilizing force (Figure 17). This concurs with postural research that indicates that the preparatory recruitment of the lower extremity musculature is primarily responsible for maintaining whole-body stability (Cordo and Nashner, 1982; Bouissett and Zattara, 1987; Massion, 1992). Anticipatory activity of the postural muscles was accompanied by a shift in the CoP displacement, which provides evidence of APAs (Figure 13).

In anticipation of Symmetrical loading, the CoP was displaced in the anterior direction, the direction of the impending anterior perturbation (Figure 13). The symmetrical, bilateral activation of the left and right Soleus muscle pair, activated at a level of 10% MVC, generated a plantar flexor moment about the ankle joint, causing a forward shift in the AP CoP displacement, and an anterior displacement of the CoP (Figure 16). This AP APA concurs with previous studies in which a forward flexion of the trunk, and a plantar flexor moment about the ankle joint, were observed in anticipation, and then in response, to the postural perturbation in an effort to counteract the destabilizing forward moment (Crenna et al., 1987; Nashner, 1982; Oddsson and Thorstenson, 1986; Horak and Nashner, 1986). The rationale for the anticipatory response of the CoP, is that a forward shift effectively increases the moment arm between the CoM and the CoP, enabling an external moment to be generated that extends the body to maintain its stability. The intent of this whole-body moment is to maintain the CoM
within the base of support, or at the very least minimize or dampen the destabilizing anterior perturbation. This anticipatory response in the control of voluntary trunk and whole-body movements has been observed previously (Oddsson, 1990; Oddsson and Thorstenson, 1986; Toussaint et al, 1997).

It was also found that the AP APA was dependent on the knowledge of timing to load onset. Figure 13 depicts the increased anterior displacement of the CoP prior to load onset for the Expected timing condition. This shows evidence of a feedforward postural adjustment that was elicited based on knowledge of the direction, timing and magnitude of the perturbation. Do et al. (1991) have found that APAs themselves are a perturbation to the initial equilibrium. It can be inferred that the pre-emptive displacement of the AP CoP did not compromise whole-body stability to an unstable degree, as subjects did not exhibit loss of balance. Yet it is not known whether postural stability would have been compromised if the load were not added.

Prior to the Asymmetrical loading, the CNS evoked bilateral differences in the BF and Soleus muscle pairs (Figure 17). This was evident by the greater change in the anticipatory EMG levels for the right side, as compared to the left side, for both lower extremity muscle groups. The muscular anticipatory response was accompanied by a lateral displacement of the ML CoP prior to the Asymmetric load onset as depicted by the pre average position of the ML CoP in Figure 10. Riedyk et al. (1999) have also observed joint moments that served to move the CoP in a lateral direction to control and counter the lateral collapse of the trunk in response to an Asymmetric perturbation. It can be concluded that by displacing the CoP more laterally, the destabilizing effect of Asymmetric loading on whole-body equilibrium was minimized, as the lateral moment
arm of the perturbation was reduced. It is noteworthy to add that the anticipatory response of the ML CoP was not significantly affected as a result of load symmetry or timing variables. The absence of a ML APA may be attributed to the substantial challenge to the whole-body stability caused by the Asymmetric perturbation loading, impeding the ability to execute a fully expressed ML APA. In attempting to react to the imposed anterior-lateral instability, the CNS may have forgone the APA. To substantiate this conclusion, McIlroy and Maki (1999) found limited effect of ML APAs in preserving lateral stability during anterior-posterior perturbation trials.

Bilateral activation and co-contraction of the trunk and leg muscles, prior to load onset, were also among the preparatory strategies evoked by the CNS to preserve whole-body stability. Muscle stiffness, reflected as EMG activation, provides immediate resistance to whole-body perturbations by increasing compression about a joint and subsequently increasing stability (Janevic, Ashtom-Miller, and Schultz, 1991; Cholewicki and McGill, 1996). Nashner et al. (1979) attributes muscle stiffness, modulated by activating muscle tissue, as an initial strategy in resisting an external perturbation or equilibrium disturbance. To re-iterate, muscle stiffness and co-activation are strategies evoked by the CNS to anticipate and resist an external force or equilibrium perturbation (Rack and Westbury, 1974; Crisco and Panjabi in Winter, 1990; Cholewicki and McGill, 1996).

Bilateral activation, as a preparatory strategy, was evident by the pre averages of the BF and Sol muscles prior to load onset. The magnitude of the pre activation level did not exhibit any functionally relevant bilateral differences (refer to Table 3). Each muscle exhibited an increased activation relative to resting activity just prior to the load
perturbation, regardless of the effects of timing or load symmetry. Values for the pre- 
average activation magnitudes, collapsed across side, were as follows: 8% MVC for BF, 
10% MVC for Sol and 4% MVC for TA (Appendix B: Table 3). These pre averages 
further substantiate the anticipatory response, as the increased muscle activity leads to 
increased muscle stiffness. By stiffening the leg muscles prior to the load onset the 
whole-body stability is increased (McGill, 1992; Henry et al., 1998; Cholewicki et al., 
1999; Carpenter, Frank, Silcher and Peysar, 2001).

However, anticipatory responses of the BF and Sol muscles were significantly 
affected by load symmetry. Symmetrical loading was anticipated with symmetrical 
activation of the right and left sides for both the BF and Sol leg muscle groups (Figure 
17). Yet, as noted previously, differences were evoked between bilateral muscles pairs 
in anticipation of the Asymmetrical load for the BF and Sol muscles (Figure 17). This is 
consistent with postural studies finding that APAs are elicited based upon the expected 
parameters of the perturbation (Bouisett and Zattara, 1981; Aruin and Latash, 1995b).

Co-contraction, of the Sol and TA agonist and antagonist muscle pairs acting 
about the ankle joint, was also imperative in resisting the destabilizing forces in the AP 
direction (Appendix B: Table 4). As another anticipatory postural strategy, the pre-
activation of the Sol (10% MVC), in addition to the tonic level of TA (4% MVC) resulted 
in co-contraction of the agonist-antagonist muscle pairs and increased mechanical 
rigidity, (Horak and Nashner, 1986, Oddsson and Thorstenson, 1986; Aruin and Latash, 
1995a). Relatively higher activity of the Sol muscle generates a plantar flexion moment 
about the ankle to move the CoP anterior to the CoM, and acts in combination with the 
low tonic activation of the TA, which opposes forward movement of the trunk. This
well-documented postural strategy, termed the 'ankle strategy', increases resistance to the anticipated perturbation by pre-emptive increase in ankle stiffness, and maintains postural alignment by moving the CoP in front of, or beyond, the CoM (Winter, 1995; Horak and MacPherson, 1997; Latash, 1998; Stanley et al., 1998).

It is also interesting to note that, of all the leg muscles recorded, the BF was the only muscle to show a significant anticipatory response (Figure 14). Activation of the BF flexed the knee and moved the trunk backwards in anticipation of the postural perturbation, thus moving the CoM posterior (Horak and Nashner, 1986). This postural strategy, termed the 'hip strategy', was implemented by the anticipatory activation of the trunk muscles (Figures 14 and 15) and active torques at the hip joint (Figures 14 and 17), superimposed upon the ankle muscle activation (Figure 17).

Compensatory Responses

Postural adjustments are elicited to regain whole-body equilibrium upon being exposed to an external perturbation similar to hand loading used in the current study. Unpredictability of the perturbation impairs the ability of the CNS to prior plan an effective APA that would minimize the destabilizing effect on whole-body postural stability. The peak activity for all muscles recorded was higher in the Unexpected timing condition, relative to the Expected timing condition (Figure 23). The increased magnitude of activation was most evident in the Surprise condition, for example the Sol exhibited a peak response of 40% MVC in the surprise trial and 25% MVC in the Unexpected experimental condition (Figure 28). The more elevated muscle activity
during the unanticipated Surprise trial, can lead to increased compressive loads on the spine and the increased risk of injury (Lavender et al., 1993; Lavender and Marras, 1995; Magneusson et al., 1996). It can be assumed that this increased force generation is associated with an insufficient anticipatory activation or resistance to the load perturbation in the Unexpected condition (Rack and Westbury, 1974; Cholewicki and McGill, 1995). The relative magnitude of the perturbation remained similar for both expectancy conditions, as the load perturbation magnitude remained constant. Thus, when the perturbation was anticipated, preparatory responses pre-activated the lower extremities prior to the load onset, generating the CoP displacement that adjusts the mechanical stability of the whole-body to minimize the CoM displacement in response to the perturbation. For the Unexpected timing condition there was inadequate warning time prior to the load onset, necessitating higher compensatory responses to regain the CoM position following the sudden loading. Lavender et al. (1993) and Thomas et al. (1998) also found that overall postural disturbances were highest in the Unexpected loading conditions.

Exposing subjects, in bilateral stance, to these external postural perturbation also elicited relatively stereotypical recruitment patterns of the leg and trunk muscles. Nashner et al. (1979) determined that rapid postural adjustments of the leg muscles to postural perturbations exhibited muscle onset latencies within the range of 95 to 120 msec, following the load onset. Recruitment of postural strategies in response to the handheld load applied in the current experiment reached peak activation within the range of 120 – 250 msec latencies following the load onset (Appendix B: Table 4). The difference between muscle onset latencies and the peak latencies recorded in this study
should be noted. Most postural research refers to muscle onset latencies, which are typically shorter and characterize the initial activation of the muscle. The times-to-peak variable indicated how fast the muscle responded to a perturbation, the peak response time. Both variables represent temporal recruitment patterns of muscular activation to in response to a postural displacement (Deiner, Dichigans, Bootz and Bacher, 1984).

Anterior – Posterior Stability

In response to the Symmetrical perturbation, which compromised whole-body stability within the AP plane, the postural adjustment displaced the body CoM in the posterior direction, while attempting to keep the trunk aligned with the lower extremities. The peak response of the AP CoP was dependent upon the knowledge of load timing (Figure 21). With sufficient warning prior to the perturbation, the anticipatory response displaced the CoP in the anterior direction and effectively minimized the peak disturbance of the CoM. Yet under Unexpected timing conditions, the mean absolute peak amplitude CoP displacement was 1 cm larger in the anterior direction. AP stability was compromised to an even greater extent during the Surprise condition, as the peak AP CoP was displaced an additional 1 cm beyond the displacement in the experimental condition. Thus, it can be inferred that whole-body equilibrium and CoM stability were compromised to a greater extent when the load was not anticipated. As a result of insufficient preparatory strategies before the load was dropped, all of the postural adjustments necessary to regain postural equilibrium were required to occur after the load onset.
Symmetrical loading evoked bilaterally equal peak responses of the BF and Sol muscles (Figure 26). Similar to the activation trends of the pre averages and anticipatory response, both sides of the body were activated equally to counteract the destabilizing forward moment due to the forward flexion trunk moment that was induced, and the equal distribution of the load between the right and left sides of the body. This increase in the activation of posterior muscles, in response to an anterior perturbation, has been well documented (Nashner, 1982; Bouisset and Zattara, 1987).

In response to the AP perturbation, there was a distal-to-proximal activation pattern as the activity began in the muscles controlling the ankle joint and then radiated in sequence from the distal to proximal joints (knee to spine). In response to the Expected condition, the muscle activation sequence began in the ankle muscles and then radiated, in sequence, to the thigh and then the trunk muscles (Appendix B: Table 6). This stereotypical response restored equilibrium by moving the body CoM primarily around the ankle joints (Nashner, 1982; Horak and Nashner, 1986). Yet, for the Unexpected timing condition an alternative temporal recruitment pattern was evoked, as the Sol reached a peak amplitude response at 135 msec, followed by the TA at 180 msec (Figure 31).

Of all of the muscles recorded, the effect of timing on the times-to-peak was significant for the Sol and TA only, confirming their role as a first line of response to postural AP instability. Due to the unpredictability of the Unexpected load onset there was not sufficient anticipatory modulation of muscle stiffness about the ankle joint. The agonist (Sol) reacted to the loading perturbation and reached its peak prior to the antagonist (TA). Deiner et al. (1984) also observed that agonists, characterized by short-
latency responses, were more functionally adaptive and responded more rapidly to an anterior perturbation than the antagonists, which typically elicit longer-latency reflexes. It may be concluded that peak latencies temporally recruited a reflex-mediated response to resist the unexpectedly induced anterior perturbation, followed by the peak response of the antagonist.

*Medial – Lateral Stability*

Lateral stability was compromised only under Asymmetric loading conditions, in which the load was applied in both the anterior and lateral directions. Figure 22 depicts a more lateral displacement in response to the Asymmetric loadings. Again, the magnitude of the ML CoP displacement was dependent on anticipation of the load onset. Unexpected perturbations elicited larger peak lateral CoP displacement responses. Similar to the Symmetric condition, this reflected insufficient anticipatory stiffness prior to the ML perturbation, necessitating full recovery of ML stability after the load onset.

Similar to the anticipatory responses, bilateral asymmetries were evoked between the contralateral and ipsilateral leg muscles in response to the Asymmetric load placement. To the contrary, the Surprise condition did reveal bilateral asymmetries that were elicited in the experimental trials under Asymmetric conditions. Figure 28 illustrates bilateral co-activation of the right and left sides of the Sol muscle pair under the Asymmetric Surprise condition. It may be inferred that, as a result of the completely unanticipated nature of the perturbation, the CNS was not able to respond efficiently to the Asymmetric perturbation and, rather, settled on a co-activation and increased muscle
stiffness strategy to regain stability (Crisco and Panjabi in Winter, 1990; Winter et al., 1996; Cholewicki and McGill, 1996). Carpenter et al. (2001) also reported that under conditions of postural instability, analogous to the surprise condition, the CNS adopted the muscle stiffness strategy to restore biomechanical equilibrium.

In response to the lateral perturbation, there was a progressive recruitment pattern from distal-to-proximal that initiated at the ankle joint and followed at the hip joint and trunk muscles. The first muscle to reach its peak was the TA, 169 msec, followed by the recruitment of the BF and Sol at 187 msec, TES at 190 msec, and LES at 205 msec, after the load onset (Appendix B: Table 6). The response was characterized, in part, by both the ‘ankle’ and ‘hip’ strategies. Biomechanically, the ankle muscles cannot produce as large of a moment as the hip muscles due to smaller moment arms and cross-sectional area. It is proposed that the proximal muscles acted to move the body CoM, while the distal muscles at the ankle stabilized the lower extremities themselves (Henry et al., 1998).

The control of lateral CoM equilibrium differed in the Surprise condition from the experimental results. The Asymmetric Surprise condition recruited the right, ipsilateral BF at an onset latency of 125 msec, followed by the right, ipsilateral Sol at 142 msec and TA at 180 msec times-to-peak (Figure 32). Thus, the postural response consisted of marked hip extension to move the CoM quickly by bending the trunk backward, characteristic of the ‘hip strategy’ (Nashner and MacCollum, 1989; Horak and Nashner 1986; Winter, 1995; MacPherson and Horak, 1997). However, there was a discrepancy in that the time-to-peak for the LES muscle was 250 msec for the right side. Typically the ‘hip strategy’ is implemented by adding early trunk muscle activation and active
moments about the hip joints, superimposed with the ankle muscle co-activation (Winter, 1995; Horak and Nashner, 1996; Henry et al., 1998). The modified ‘hip strategy’ may have been adopted due to its efficiency and capability to move the body CoM, relative to the ankle musculature. Horak and Nashner (1986) demonstrated that in distinct postural strategies may be combined to synthesize a continuum of different postural adjustments. It may also be assumed that the delay of the trunk extensors was indicative of the CNS prioritizing whole-body stability prior to trunk stability due to the magnitude of instability.

Results from the current study suggest that the control of postural equilibrium may be similar for anterior and lateral perturbations, although specific differences in patterns may reflect various biomechanical constraints of the trunk and lower extremities associated with the two planes of movement. To the contrary, Winter et al. (1996) suggested that, in the AP and lateral planes, equilibrium control occurs by different, independent mechanisms. Accordingly, in quiet stance, ankle stiffness is responsible for the sagittal plane and the hip mechanism is responsible for medial-lateral equilibrium. The times-to-peak data of the current study refute this conclusion as ML instability was regained based upon a combination of the ‘hip’ and ‘ankle’ strategies.

Evidence for the inference of a similar postural control mechanism for the sagittal and frontal planes is associated with the CoP displacement, which was observed to have similar time-to-peak responses in both AP and lateral directions and for all combinations of load symmetry and expectancy. Given that the load perturbation was standardized in magnitude for the current experiment, the mean absolute magnitude of the CoM displacement was similar, regardless of the direction of perturbation. The difference in
postural reflexive responses elicited to regain CoM stability for the AP and ML planes was within the temporal muscular recruitment and muscular activation levels of the neuromuscular system (Rietdyk et al., 1999). Therefore, it is concluded that the differing reflex-mediated responses were made based upon anatomical constraints, and the functional requirements of balance in the AP and ML planes, rather than postural control strategy.

**Trunk Stability**

*Anticipatory Response*

Most of the changes in the pre averages and the anticipatory responses prior to the sudden load were the result of the affect of load symmetry. Neuromuscular preparations to a biomechanical trunk perturbation were also regulated by the knowledge of the timing of impact. For clarity, a schematic diagram of the cross-sectional area of the trunk is provided, illustrating all of the muscles recorded in the study, labeled regarding functional roles and relations among the muscles groups. The diagram depicts the positioning of load placement complexities.
Figure 33: An overhead cross-sectional view of the lumbar spine. Anterior refers to the front of the body, while Posterior refers to the back of the body. Load circles indicate the direction of forward flexion for the Symmetrical condition, and the forward flexion with lateral bend for the Asymmetrical loading conditions.

**Expectation**

In anticipation of the load onset, both the TES and LES muscle pairs elicited greater pre averages and anticipatory responses under the Expected timing condition (Figures 11 and 14). It is worth noting that this increase in muscle stiffness is similar to the pre-emptive increase that was observed in the BF and Sol posterior leg muscles prior to load onset. It appears that common CNS strategies were implemented to minimize instability in both the whole-body and the trunk. Results from this study also showed significantly higher anticipatory responses of the left lateral agonists (ExO) and right flexor stabilizers (InO) prior to the Expected sudden load perturbation, regardless of load
symmetry (Figure 16). When the timing of a sudden load can be anticipated, it is assumed that increased co-activation of the trunk muscles is modulated to stabilize the trunk and reduce the equilibrium disturbance and kinematic displacement (Bouissett and Zattara, 1987; Lavender *et al.*, 1992b; Lavender *et al.*, 1993; Thomas *et al.*, 1998). Granata, Orishimo and Sanford (2001) did not observe differences in anticipatory co-active muscle recruitment patterns between expected or unexpected load timing conditions. Methodological factors may have contributed to the results. Granata *et al.* (2001) used a load impulse that was normalized to 2.5% MVC of each subject’s maximal lifting capacity dropped from a height of 0.5m. The magnitude of this load impulse was of markedly less amplitude than the sudden load applied in the current study and in previous sudden loading research protocols.

*Symmetrical Loading*

In anticipation of the Symmetric loading there were no bilateral differences observed in the anticipatory response of any of the trunk muscles recorded (Figure 15). The Symmetrical load placement involved both erector spinae muscles as primary agonists and the oblique muscles as trunk stabilizers (Figure 33). Thus, the pre average response evoked bilaterally equal pre-emptive activation of all the trunk flexor agonists and antagonists or stabilizers prior to the anterior perturbation (Figure 12). As the muscle stiffness was increased, the mechanical stability of the trunk increased due to increased muscle stiffness and joint compression about the lumbar spine (Panjabi *et al.*, 1989;
Crisco and Panjabi in Winter, 1990; Cholewicki and McGill, 1996; Gardner-Morse and Stokes, 1998; Thomas et al., 1998; Stokes, Gardner-Morse, Henry and Badger, 2000).

The erector spinae muscles were found to be most effective as agonists to the anteriorly placed load (Figure 33). Both the left and the right LES and TES muscle pairs were found to generate the highest pre-activation level in anticipation of counteracting the Symmetrical perturbation (Appendix B: Table 6). This concurs with previous research that observed the erector spinae muscle group were the definitive agonist in response to an anterior load that evoked a flexor moment of the lumbar spine (Lavender et al., 1992b, vanDieen, 1996).

As indicated, bilateral co-activation of the trunk stabilizing oblique muscles was recruited to augment spinal stability (Figure 15). McGill and Norman (1996) also concluded that the lateral portions of the oblique muscle groups were recruited, in addition to the erector spinae, to increase resistance and trunk stiffness prior to onset of the anterior load perturbation.

Asymmetrical Loading

The Asymmetrical load placement caused a forward flexion of the trunk, in addition to a right lateral bend moment, which elicited a complex activation pattern of the trunk musculature. To resist the anterior and lateral portions of the load, the left erector spinae muscle group responded primarily as agonists. The left internal and external obliques were also activated, in part, as lateral agonists to the Asymmetric load placement (Figure 33). Other trunk muscles were also recruited to stabilize the spine.
even though their activation was antagonistic with regards to resisting the applied asymmetric moment (Lavender et al., 1995). The right internal and external obliques were antagonistic to both Symmetrical and Asymmetrical loads and responded solely as trunk stabilizers. The right erector spinae muscle group also served as a stabilizing role in an effort to resist lateral bending. In addition to a lateral agonistic function, the left side of the oblique muscle group was recruited to provide antagonistic resistance to the anterior portion of the Asymmetric perturbation (Figure 33).

Under the Asymmetric condition, the primary role of the lateral agonists was confirmed by the pre-activation of both the left LES and ExO, which were greater than on the right side (Figures 12 and 15). The results indicate that the pre average of the left LES was higher than the left ExO (Figure 12). In a study that observed the trunk muscle response to prolonged, isometric, lateral bend moments, Potvin and O"Brien (1998) found that the highest agonist activation was the left ExO, followed by the left InO, LES and TES (for the muscles observed in the current study). A plausible explanation for the higher pre-activation of the left LES muscle, than the left ExO in the current study was because the LES is an agonist to extension and left lateral bend, while the EO is an agonist to left lateral bend and an antagonist to extension. However, it may be concluded that the contralateral LES and ExO were both necessary to resist the Asymmetric loading, given the current method of applying the lateral bending moment with a hand-held load. In studies that implicate the erector spinae as the sole lateral agonist, the load was applied via a chest strap evoking a pure lateral bend (Lavender et al., 1994; Chiang, 1997). Although lateral bending moments have been applied using either method, the hand-held
load held away from the body required both the erector spinae and obliques to balance the spine due to the resulting combination of flexor and lateral moments.

In anticipation of an Asymmetric load, the TES has also been shown to resist a lateral bending moment, although to a lesser degree than the LES (Lavender et al. 1992; McGill, 1992). Yet, in the current study the TES was observed to have a unique activation pattern from the left LES and ExO, lateral agonists. The pre average of the right TES, a flexor agonist and lateral stabilizer, showed higher activity relative to the left side (Figure 12). The right InO, which served only as a trunk stabilizer, also elicited an asymmetrical anticipatory response with the right side activation being higher than the left (Figure 15). The lateral stabilizer muscles, (right TES and InO), were also observed to have increased anticipatory activation levels when the timing was expected, which further validated the preparatory co-activation strategy (Figure 16). It may be assumed that this anticipatory increase in the right TES and InO served a functional role in trunk stability. Potvin and O'Brien (1998) also showed that the TES was mostly recruited for an antagonistic stabilizing function and a minimal agonistic contribution to resisting a lateral bending moment to the right.

A plausible explanation for the pre-emptive activation of the lateral stabilizers is the necessity to counter the activation of the lateral agonists and equilibrate the moments acting about the spine prior to load onset. The pre-average activation levels, for the right TES (Figure 12) and InO muscle pairs, were 18% and 10% MVC respectively. This increase in muscle stiffness is assumed to increase the overall stability of the trunk prior to the load onset (Rack and Westbury, 1974; Bergmark, 1989; Cholewicki and McGill, 1996). It is duly noted that the pre-averages of trunk stabilizers, the right TES and InO,
were marginally higher than the pre averages of the lateral agonists, the left TES, LES and ExO. The cumulative effect of the co-activation of the trunk agonists and stabilizers is hypothesized to increase the lumbar compression at the spine (Crisco and Panjabi in Winter, 1990). It is thought that the anticipated compression forces acting on the spine, lead to increased lumbar stiffness and reduced flexibility. This could reduce the required muscular response to the pending Asymmetric perturbation.

Conversely, the Asymmetric Surprise condition evoked anticipatory recruitment strategies that differed from the Experimental trials. The most dramatic change was noted in the TES, as the left (agonistic) side elicited a higher anticipatory response than the right (stabilizing); side (Figure 18). It is hypothesized that by activating the left TES, more than the right side, the left TES acts as a lateral agonist and resists the Asymmetric load, compromising trunk stability. This theory will be re-visited in the discussion of the peak response evoked during the surprise condition.

Compensatory Responses

Expectation

In response to the Expected sudden loading, regardless of load symmetry, all of the trunk muscles elicited peak responses that were smaller in amplitude than for Unexpected loading (Figure 23). With temporal knowledge of the load onset, pre averages of the TES, LES, InO and ExO muscles minimized the impact of the destabilizing perturbation, both Symmetric and Asymmetric (Figure 12). Again the CNS employed the preparatory strategy of increasing stiffness that decreased reflexive responses and kinematic displacement of the trunk and whole-body equilibrium (Marras
et al., 1987; Lavender et al., 1989; Lavender et al., 1993; Thomas et al., 1998). Similar to compensatory, postural reflex responses elicited to regain whole-body stability; Unexpected load perturbations evoked greater peak responses. The increased activation was most evident in the Surprise condition; for example, the InO exhibited a peak response of 34% MVC in the Surprise condition, and 15% MVC in the Unexpected experimental condition (Figure 27). The increased muscle activity associated with the sudden, Unexpected perturbation concurs with the findings of Marras et al. (1987), Lavender et al. (1993), Cresswell et al. (1994) and Thomas et al. (1998), among others. Cholewicki and McGill (1996) have hypothesized that these compensatory responses lead to increased compressive loads on the lumbar spine and cause overloading of a single tissue, thus leading to injury.

Symmetrical Loading

In response to Symmetrical loading, the right and left sides of all of the monitored trunk agonists and stabilizers were co-activated. The TES demonstrated the largest peak response of all of the sampled trunk muscles during sudden loading (Figure 23). The most apparent functional role of the TES was as an agonist to counter the forward flexion of the trunk induced by the Symmetrical conditions.

In response to the Surprise Symmetrical perturbation, LES and ExO were the only trunk muscles activated equally on the right and left sides, adopting a co-activation strategy to regain stability (Figure 26). The right TES and the bilateral LES muscles were required to resist the forward moment and regain trunk stability (Figure 24).
Asymmetries, observed in the activation of the TES and InO bilateral muscles, may be the result of conflict between their roles as trunk stabilizers and agonists.

Under Symmetrical loading there were marginal differences between the peak latencies of the anterior and posterior trunk muscles. It may be inferred that trunk stability was maintained via co-contraction of the trunk agonist and stabilizer muscle pairs. Thomas et al. (1998) observed that the EMG onset rate of the posterior muscles always preceded the anterior muscles in the Expected loading condition. It may be assumed that due to its early onset, the erector spinae muscles would have a lower time-to-peak than that observed in the current study. It is noteworthy that Thomas et al. (1998) studied the effects of sudden loads applied directly to the torso via a harness, with motion limited to the lumbar spine. An anterior perturbation applied via a chest strap would generate a pure forward bending moment of the spine. In the current study, the Symmetrical perturbation was applied to hand-held load, which will also introduce substantial compression forces onto the spine, which may lead to simultaneous peak activation of the trunk muscles.

Asymmetrical Loading

Asymmetric loading elicited similar patterns of asymmetry as previously discussed for the anticipatory response. The left side LES and ExO muscles had higher activation levels than the side right, as these muscles were contralateral to the load placement and counteracted the lateral perturbation (Figure 26). The Asymmetrical peak response of the bilateral TES was similar to that observed for pre-activation (Figure 24).
The mechanical action, and the results of McGill (1991), would suggest that the right TES served as a stabilizer in response to the Asymmetrical load.

Asymmetrical loading elicited higher activation of the trunk lateral agonistic muscles, referring to the left side of all of the trunk muscles sampled (Figure 33). The peak response in the Surprise condition mirrored the response to Asymmetric loading in the experimental conditions for the LES and ExO muscle pairs (Figure 26). However, the InO and TES were both activated as lateral agonists, as opposed to the stabilizing function elicited in the Asymmetric experimental conditions. The left InO and TES were required to resist the Asymmetrical load perturbation with a greater increase in the left side than the right side (Figures 24 and 27). This result poses a contradiction at a time when maximum stability would be assumed to be required for the spine. A plausible explanation for recruiting both the TES and InO to resist and counter the Asymmetric load in the Surprise condition, was the degree of instability imposed on the whole-body, given the unpredictability of the perturbation. Again, without any sort of temporal warning, all of the trunk muscles were prioritized to counter the Asymmetric perturbation. This recruitment pattern contradicted the optimization of trunk stability. Thus, it may be interpreted that in circumstances when the postural equilibrium is challenged to such an extent, the control of whole-body stability was made a priority over trunk stability. It is also important to note that the risk of injury may be higher in cases where the load is completely unexpected because the importance of stability seems to take a back seat to perturbation resistance.

In response to the Asymmetric perturbation, the lateral agonist trunk muscles each reached their relative peak response at a latency of 185 – 200 mesc (Figures 30 and 32).
The times-to-peak response were as follows; initially the left ExO with a time-to-peak latency of 185 msec, followed by the left TES at 190 msec and the left LES with 205 msec latency. These lateral agonist muscles collectively act to resist the forward and lateral bend of the trunk and regain trunk stability. It is interesting to note that the left TES was activated within the same temporal sequence as the agonistic trunk muscles, while its functional role in the anticipatory and compensatory response was as a trunk stabilizer. This may reflect the trunk muscles' initial priority in resisting and countering the sudden perturbation prior to maintaining and optimizing trunk stability.

Under both Symmetric and Asymmetric conditions, the InO was the last of the trunk muscles to reach its peak response (Figure 30). During the Expected timing condition the right side had a lower time-to-peak than the left side. It is proposed that this represents the stabilizing function of the InO, as with knowledge of the anticipated perturbation the trunk muscles were able to prepare to counter the external force and optimize trunk stability. When the timing was Unexpected the left side revealed a lower time-to-peak than the right side. The change in the muscle recruitment may reflect the need to react to the postural perturbation initially, neglecting to optimize trunk stability.

In response to the Surprise condition, the TES was the first trunk muscle to be recruited. Contrary to the experimental condition, both the right and left times-to-peak were similar. The temporal recruitment pattern for the Asymmetrical Surprise was as follows: the left TES with a 130 msec time-to-peak, followed by the left LES with 210 msec time-to-peak. At approximately 250 msec both the oblique muscles reached their respective times-to-peak (Figure 29). The temporal response of the flexor agonists and lateral agonists coincide with the time-to-peak of the BF, validating the hip strategy as
the proximal and trunk muscles were activated prior to the ankle joint (Nashner and McCollum, 1985; Horak and Nashner 1986; Winter, 1995; Horak and MacPherson, 1997).

Conclusions

Based on the results of this study, it is possible to summarize a number of trends and activation patterns that were observed for both trunk and whole-body stability. Some of the following findings are re-affirmations of the neuromuscular anticipation and response to load perturbations, determined in other research studies. These principles were found to govern the anticipatory adjustments and reflex-activated compensatory strategies, and were upheld by both systems. Thus, unless otherwise stated the below statements are applicable to both trunk and leg muscles, summarizing both trunk and whole-body stability. Unique to the current study was the integration and interaction of trunk stability and whole-body postural control, allowing the control of equilibrium to be facilitated as a global system.

Expectancy

- With knowledge of load timing, increased pre-activation was observed and this was concluded to cause higher muscle stiffness and enhanced resistance to the perturbation. This served to decrease the displacement of the body CoM.
• Unexpected loading conditions were associated with lower pre-activation responses, which necessitated higher increases in EMG amplitude in response to the perturbation, for both flexor and lateral agonists and stabilizing antagonists, and compensatory postural CoP

*Anticipatory Postural Adjustments*

• Given the prevalence of an AP APA and the absence of a ML APA, it was concluded that the control of APAs was dependent upon the expectancy of load onset and the various biomechanical constraints in the AP and ML planes of movement.

*Anterior – Posterior Stability*

• Anterior perturbations stereotypically evoked bilaterally symmetrical responses, given that the load was equally distributed between the right and left sides of the body.

• Lower tonic levels of stabilizing, anterior muscles were accompanied with increased activation of the flexor agonists of both the trunk and leg muscles. Co-activation of agonist and antagonist muscle pairs, thereby increased compression forces and attenuated joint rotations induced by loading perturbations.
Medial – Lateral Stability

- To prevent the collapse of ML stability, the ipsilateral leg muscles were more highly activated than the contralateral side. Asymmetrical activation patterns were found to alter the shear forces acting at the supporting surface and regain whole-body stability.

- A co-activation strategy regulated the trunk muscles prior, and in response, to Asymmetric loading. Lateral agonists were activated in co-ordination with lateral stabilizers to increase mechanical rigidity and ensure spinal stability.

Times-to-Peak Response

- The temporal recruitment patterns for all of the monitored agonist and stabilizing muscles elicited similar times-to-peak upon regaining stability and were therefore not affected by expectancy of load onset.

- There was an underlying distal-to-proximal muscle activation pattern that was initiated about the ankle, and in conjunction with early proximal (hip and trunk) muscle activation for both load symmetry conditions.

The CNS implemented the above compilation of strategies for the purpose of maintaining trunk stability and whole-body postural control. The recruitment and activation patterns of the muscles examined were characterized by bilateral activation and co-activation trends. The most frequent anticipatory adjustment adopted was the modulation of muscle stiffness, which provides immediate resistance to the pending perturbation. Increased muscle stiffness prior to load onset, determined the reflexive compensatory response necessary to regain stability (Nashner and Cordo, 1981; Nashner,
In response to the load perturbation, co-activation of trunk and leg agonists and antagonists were recruited to increase compression and subsequently increase stability. In summary, postural and trunk equilibrium are achieved by similar control mechanisms for sagittal and lateral control of the body CoM.

Thus, it is arguable that similar mechanisms facilitate the control of whole-body and trunk stability. Results from the current study imply that both systems optimized stability, each according to their individual measures: whole-body stability by the position of the body CoM, within the BoS and trunk stability by critical stiffness and mechanical equilibrium about the lumbar spine. Although trunk stability and whole-body postural equilibrium are functionally independent, control of the two systems are very much integrated. Temporal recruitment of muscles, in response to a postural perturbation, provided evidence of this. A continuum of postural strategies, characterized primarily by the distal-to-proximal muscle activation pattern initially recruited muscles to stabilize the ankle, in co-ordination with early proximal, trunk or hip, muscle activation, regardless of the load symmetry or timing variables. Thus, spatial and temporal recruitment patterns, necessary for whole-body stability, were integrated and coordinated with compensatory responses that were used to regain trunk stability.

The integration of the control of trunk and postural stability was challenged in the Surprise condition, as the postural threat was completely unpredicted. During these trials, stability was highly compromised and whole-body equilibrium jeopardized. Compensatory responses of both trunk and leg muscles were primarily recruited to counter the postural perturbation and regain the loss of equilibrium. This contradicted the activation patterns elicited under the experimental Unexpected conditions, in which the
reflex-activated trunk muscle responses optimized trunk stability, in collaboration with resisting the postural perturbation. Thus, it may be interpreted that, in circumstances where the postural equilibrium withstands a completely unexpected perturbation, the control of whole-body stability was made a priority over trunk stability.

It was also hypothesized that the destabilizing effects of Asymmetric loading and Unexpected sudden loading would be compounded and compromise whole-body equilibrium to a magnified extent. Both load asymmetry and unexpected timing, required greater neuromuscular control to maintain stability. It was assumed that the interaction of Asymmetry and Unexpected timing would amplify the amount of antagonistic co-contraction necessary to achieve spinal and whole-body stability. The results of the study did not support this proposed interaction. It may be interpreted that the CNS evaluated the severity of all effects of load symmetry and expectancy and gave priority to the compensatory strategy that would reduce the most destabilizing possibility. In response to either of the destabilizing effects, the stiffness generated to regain stability may be sufficient to counter both aspects of the perturbation. From these observations, it may be concluded that, in the control of whole-body equilibrium, the reflex-activated compensatory responses are evoked to respond in order of priority. The greatest postural threat to whole-body stability is prioritized.

The current experimental design allowed for the two systems, trunk stability and whole-body postural control, to respond and interact without inhibitions. Similar mechanisms were observed to govern the control of both trunk and spinal stability in response to the load symmetry and timing perturbations. This suggested that the control of whole-body and trunk stability were regulated in parallel. Anticipatory and
compensatory responses, that were evoked to maintain stability, were concluded to integrate whole-body and trunk stability, indicating that the two systems do not act in isolation of one another. In conditions of high postural threat, such as the Surprise condition, whole-body stability was found to take precedence over trunk stability. The control of whole-body equilibrium was also observed to prioritize the potential destabilizing factors and respond to the greatest postural threat. Thus, trunk and whole-body stability were not mutually exclusive, but rather were integrated to optimize the control of whole-body equilibrium.

Recommendations for Future Research

Whole-body equilibrium and trunk stability are both of paramount importance to the maintenance of vertical upright posture and the performance of activities of daily living. Ultimately, the combination of whole-body equilibrium and trunk stability results in the successful execution of goal-directed movements. Given that this study was the first to investigate the integration of whole-body postural stability and trunk stability, the realm of future possibilities is endless.

In the current study, the control of equilibrium was studied in a quasi-static model. It would be interesting to consider if the same principles that were found to govern stability under the current conditions would also apply under dynamic conditions. Using the current experimental design, male subjects should be considered to assess for potential gender effects. Other complexities could be considered such as older subjects or fatiguing conditions of the spine and legs prior to load perturbation onset. Rapid
unloading is another method of perturbation that could be used to assess the control of equilibrium. To further challenge the integrity of the control of stability, future studies could perturb dynamic lifting tasks, to impose conflicting requirements on the trunk muscles in the maintenance of trunk and postural stability and the execution of voluntary movements. This would provide a forum to further investigate the interaction between trunk stability and postural motor commands, as the voluntary lifting movement is also a postural perturbation. Insight from these studies may eventually identify risk factors or potential mechanisms of low-back injuries.
References


Appendix A

Information and Consent Form

Project Title: The Control of Whole Body Equilibrium and Trunk Stability During Sudden Hand Loading

Study Details:
The purpose of the study is to examine the response of whole-body control to sagittal and frontal plane loading, as it applies to trunk stability. The effects of symmetry will be investigated in combination with anticipation and load knowledge. Participants will be asked to maintain upright posture while holding a box with arms extended comfortably. The participant will not be able to see the box, which will be placed behind a black curtain hanging down to the level of the participant’s forearms. A total of eight loading conditions will be used. These conditions will be a combination of symmetrical vs. asymmetrical load placement, expected vs. unexpected timing and load magnitude knowledge vs. no load knowledge. The load will be applied to the box, held by the participant, either symmetric to, or lateral to (asymmetric) the mid-sagittal plane. In the expected condition, the participant will be verbally cued via a countdown conducted by the experimenter, prior to releasing the load. In the unexpected loading condition, the subject will receive no verbal cues of the impending load timing. The actual application of the load onset will be varied from 2 to 30 seconds. Expectation of the load magnitude will also be randomly manipulated throughout the trials. The load magnitudes used in this experiment will be scaled to body mass, as the load will evoke a perturbation that will be dependent on the subject’s inertial properties. The load will be scaled to 20 and 40% of the maximum lifting strength, for subjects of an average mass of 62 kg. Each participant will resist, in random order, eight series of loading in which the 3 conditions will be manipulated. Participants will be asked to attend one orientation session for a ½ hour and a data collection session lasting approximately 1-½ hours in length. Muscle stiffness may result after the collection, but this should be no more than may be experienced after any unaccustomed physical activity.

Consent of Subject
I have read and fully understand the information provided in this consent form and the associated information form provided to me, and voluntarily agree to participate in the described research project. I also acknowledge that I do not suffer from chronic low back pain or other low back injuries. The purpose and methods of the experiment have been fully described to me by the above-mentioned researchers. I am aware that I may report what I consider violations of my welfare to the Office of Human Research, University of Windsor, and may withdraw as a subject from the experiment for any reason at any time. I understand that my personal identity will remain confidential throughout my participation in this study. I am mindful of my right to ask for feedback on the results at the end of the study. With full knowledge of the foregoing, I agree, of my own free will, to participate in this study.

_____________________________  ________________________________
Signature of Participant                Date

_____________________________  ________________________________
Signature of Witness                 Date

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Appendix B

Summary of Statistical Findings

CoP Data
(Means expressed as displacement (cm). For AP: Positive values are indicative of anterior displacements; For ML: Positive values are indicative of displacements towards the left; Negative values are indicative of displacements towards the right.)
Degree of Freedom is always 1.

Table 1: Main Effect of Load Placement

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<th>F-value</th>
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**EMG Data**
(Means are expressed as % MVC activation).
Degree of Freedom is always 1.

**Table 3: Main Effect of Side (Bilateral)**

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