UNIVERSITÉ DE SHERBROOKE
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DÉTERMINER SI UN RÉTABLISSEMENT DE L'ÉQUILIBRE EST POSSIBLE OU SI UNE CHUTE EST INÉVITABLE POUR DEUX PERTURBATIONS POSTURALES: LE RELÂCHEMENT D'UNE INCLINAISON ET LA TRANSLATION DE SURFACE

DETERMINING IF A BALANCE RECOVERY IS POSSIBLE OR IF A FALL IS UNAVOIDABLE FOR TWO POSTURAL PERTURBATIONS: LEAN RELEASE AND SURFACE TRANSLATION

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À mes parents,

Dominique et Michel Thiaux,

Pour leur soutien inconditionnel,

Merci.

RÉSUMÉ

La grande variété de perturbations posturales utilisées dans les études expérimentales rend les comparaisons entre les études et les généralisations sur les capacités à rétablir l'équilibre difficile. En effet, seulement trois études ont tenté de comparer expérimentalement les résultats de différentes perturbations posturales et semblent démontrer que les relâchements d'inclinaison, tirages à la taille et translations de surface sont suffisamment similaires qu'elles peuvent être comparées. De plus, les expériences sur le rétablissement de l'équilibre prennent du temps, sont couteuses et potentiellement dangereuses, et peuvent être très exigeantes et fatigantes pour les personnes âgées frêles. Il serait donc utile d'utiliser un modèle plutôt qu'une expérience pour prédire théoriquement si une perturbation posturale donnée entrainera une chute inévitable ou si un rétablissement de l'équilibre sera possible pour un participant donné. Ceci semblait possible considérant que des modèles de pendules inversés ont été utilisés avec succès pour modéliser des inclinaisons, tirages, translations et trébuchements.

Pour poursuivre les travaux sur la méthode adimensionnelle de ligne de perturbation limite, nous avons déterminé l'angle maximum d'inclinaison initiale vers l'avant et la vitesse maximum de translation de surface vers l'arrière desquels 12 jeunes adultes pouvaient être soudainement relâchés ou tirés, respectivement, et tout de même rétablir leur équilibre en utilisant un seul pas. Aux angles d'inclinaison ou vitesses de translations maximum, les deux perturbations posturales n'avaient pas d'effet significatif sur l'initiation de la réponse, mais affectaient la plupart des variables d'exécution et de géométrie de la réponse. Néanmoins, les positions et vitesses angulaires à la fin du temps de réaction pour ces essais à la limite du rétablissement de l'équilibre formaient une ligne de perturbation limite qui était très similaire à celle obtenue précédemment. De plus, la ligne de perturbation limite était très efficace pour séparer les chutes (97%) des rétablissements (96%), quelle que soit la perturbation posturale.

Nous avons ensuite utilisé un modèle en deux dimensions de pendule inversé à barre mince monté sur une palette glissante bougeant horizontalement pour simuler la position et la vitesse angulaire de jeunes adultes durant le temps de réaction pour les inclinaisons et translations de l'étude expérimentale ci-dessus. La majorité des erreurs moyennes quadratiques et erreurs au temps de réaction entre les positions et vitesses angulaires expérimentales et théoriques étaient respectivement de moins de 2% et 4%. Plus important encore, les positions et vitesses angulaires théoriques à la fin du temps de réaction pour les essais aux angles d'inclinaison et vitesses de translation maximum formaient une ligne de perturbation limite séparant les chutes des rétablissements qui était très similaire à celle obtenue dans l'étude expérimentale.

La méthode adimensionnelle de ligne de perturbation limite a donc maintenant été établie expérimentalement pour les relâchements d'inclinaison, relâchements d'inclinaison avec tirages à la taille, tirages à la taille en marchant et translations de surface, fournissant ainsi des preuves additionnelles que le choix de la perturbation posturale n'affecte pas la limite du rétablissement de l'équilibre. Ceci devrait donc aider les chercheurs à faire des conclusions plus rapides et plus générales sur les capacités à rétablir l'équilibre.

Mots clefs: Chutes, Équilibre, Modélisation, Translation de surface, Relâchement d'inclinaison, Perturbation posturales.

ABSTRACT

On the one hand, the great variety of postural perturbations used in experimental studies make comparisons between studies and generalizations about balance recovery abilities difficult. In fact, only three studies have attempted to experimentally compare results from different postural perturbations and appear to shown that lean releases, waist pulls and surface translations are similar enough that they can be compared. On the other hand, balance recovery experiments are time consuming, expensive, can be dangerous and can be very demanding and fatiguing for frail older adults. It would thus be useful to use a model instead of an experiment to theoretically predict if a given postural perturbation will lead to an unavoidable fall or if balance recovery is possible for a given participant. This appeared to be possible given that inverted pendulum models have been successfully used to model lean releases, waist pulls, surface translations and trips.

To pursue the work by Moglo and Smeesters (2005; 2006) on the dimensionless perturbation threshold line method, we determined the maximum forward initial lean angle and the maximum backward surface translation velocity from which 12 younger adults could be suddenly released or pulled, respectively, and still recover balance using a single step. Results showed that at the maximum lean angles or maximum translation velocities, the two postural perturbations did not have a significant effect on response initiation, but did affect most response execution and response geometry variables. Nevertheless, the angular positions and velocities at the end of reaction time for these trials at the threshold of balance recovery formed a perturbation threshold line that was very similar to the one obtained by Moglo and Smeesters (2005). Furthermore, the perturbation threshold line was very efficient in separating falls (97%) from recoveries (96%), regardless of the postural perturbation.

We then used a two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid to simulate the angular position and velocity of younger adults from onset of perturbation to onset of response for lean releases and surface translations from the above experimental study. Results showed that the majority of root mean square errors and errors at reaction time between the experimental and theoretical angular positions and velocities were less than 2% and 4%, respectively. More importantly, the theoretical angular positions and velocities at the end of reaction time for maximum lean angle and maximum translation velocity trials formed a perturbation threshold line separating falls from recoveries that was very similar to the one obtained in the experimental study.

Therefore, the dimensionless perturbation threshold line method has now been experimentally established for lean releases, lean releases with waist pulls, waist pulls while walking and surface translations, thus providing further evidence that the choice of postural perturbation does not affect the threshold of balance recovery. It should therefore help researchers make faster and broader conclusions about balance recovery abilities.

Keywords: Falls, Balance, Modeling, Surface translation, Lean release, Postural perturbations.

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CHAPTER 1 INTRODUCTION

1.1 The importance of studying falls

In 2009, the most common cause of injuries declared by Canadians is a fall (Statistique Canada, 2010). Indeed, about 1.7 million people, representing 41% of the population sustaining an injury, declare having been hurt due to a fall.

More than 65% of the most serious injuries limiting the activities of the Canadian community dwelling elderly over 65yrs old are caused by falls, and 50% of these injuries are fractures (Statistique Canada, 1999). In addition to locomotion difficulties, which can lead to avoidance of daily activities and an increase in the risk of nursing home admission (Tinetti, 1994), personal psychological distress caused by a dependence on health services can occur. Both of these thus increase the morbidity rate of the population over 65yrs old.

In 2004, elderly people over 65yrs old represented 46% of direct costs due to falls or 2 billion dollars (Smartrisk, 2009). Moreover, elderly people over 65yrs old represented 84% of the deaths, 59% of the hospitalizations and 53% of permanent disabilities caused by falls.

The Canadian population is getting older and this tendency is verified by the inversion of the demographics since 2006 (Statistique Canada, 2005). There is indeed an inversion in the ages pyramid, showing clearly an ageing of the population over the last 50yrs (Figure 1.1). The demographic projections show that in 2015, elderly people over 65yrs old may overtake the proportion of children aged between 0 and 14yrs old. Furthermore, the number of workers per elderly people over 65yrs old has been decreasing for the past 25 years. In 1975, there were 8 adults between 15 and 64yrs old for each elderly person. This ratio is reduced to 5 to 1 in 2006 and may decrease to 2.2 to 1 in 2056. The number of elderly financed by workers is thus going to increase.

It has therefore become important to minimise expenses due to falls by attempting to prevent them. Furthermore, fall prevention has a doubly favorable impact since it will not only reduce the associated costs on society but also limit the physical and psychological impact on the elderly.

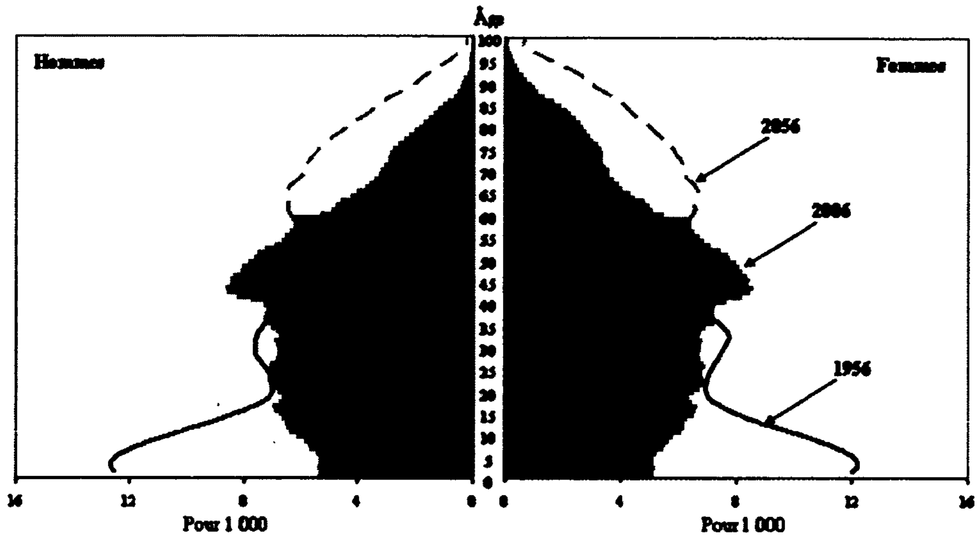

Figure 1.1: Progression of the structure by age and gender of the Canadian population (Statistique Canada, 2005).

1.2 The knowledge base on fall experiments

Numerous publications have helped to improve fall prevention by analyzing living environments (Stevens *et al.*, 2001), designing protective devices such as hip protectors (Combes and Price, 2014; Li *et al.*, 2013) or compliant floors (Laing and Robinovitch, 2009; Wright and Laing, 2011), or creating educational information (Wyman *et al.*, 2007; Yoshimura *et al.*, 2013) or exercise training (Bieryla and Madigan, 2011; Mansfield *et al.*, 2010; Robertson and Gillespie, 2013) programs.

Nevertheless, falls occur without warning and it is ethically and logistically very difficult to record these real life events with accurate instruments to quantify and characterize falls. For example, some investigators have used video capture in long term care facilities to identify the circumstances of falls but the probability of actually capturing these unpredictable events in the field of view of the cameras is small and, even when the recording of a fall is usable, data analysis is limited, not precise, very tedious and complex (Robinovitch *et al.*, 2013; Yang *et al.*, 2013). Although laboratory experiments are not totally representative of real life falls, they allow investigators to have a better control over the field of view of the cameras, a greater number of both kinematic and kinetic measurements available, and a better accuracy of all measurements taken. Fall experiments in the laboratory are thus essential.

Since falls mainly occur during activities requiring large center of mass displacements (Tinetti *et al.*, 1988), this literature review will not focus on small postural perturbations, where only feet in place balance recovery strategies are needed. Instead, we will occasionally mention medium postural perturbations, where a step is necessary for balance recovery (Hsiao and Robinovitch, 1998; Maki *et al.*, 1996; Nashner, 1980; Wolfson *et al.*, 1986), and primarily focus on large postural perturbations, where balance recovery and avoiding a fall is not always possible. These large postural perturbations are thus at the threshold of balance recovery.

During experiments, variables that characterize balance recovery from medium or large postural perturbations are usually divided in three distinct phases (Telonio and Smeesters, 2008), each with its particular importance for balance recovery depending on participant age and gender (Hsiao-Wecksler, 2008):

- *Response initiation:* These variables measure how long after the onset of a perturbation a participant initiates a response in order to recover balance. Typical variables include ground reaction force reaction times and electromyographic muscular latency times. While certain studies have shown some influence of response initiation variables on balance recovery ability (Maki and McIlroy, 2006; Smeesters *et al.*, 2001a), others have shown constant response initiation variables (Do *et al.*, 1982; King *et al.*, 2005).
- *Response execution:* These variables measure how fast a participant executes a response to recover balance. Typical variables include weight transfer time, step time and step velocity (mean or maximum). Most studies have shown constant weight transfer times (Do *et al.*, 1982; King *et al.*, 2005) and a strong influence of step times and step velocities on balance recovery ability (Maki and McIlroy, 2006; Shumway-Cook and Woollacott, 2001; Telonio and Smeesters, 2008).
- *Response geometry:* These variables measure the geometry of the response to recover balance. Typical variables include step length, step height and step width. Alternatively, the stepping angle between the two legs (α_c), the body lean angle (β_c) and the angular ratio ($AR=\alpha_c/\beta_c$) at stepping foot contact have also been used (Hsiao and Robinovitch, 1999). Most studies have shown an increase in step length with the amplitude of the perturbation (Do *et al.*, 1982; Luchies *et al.*, 1994; Maki *et al.*, 1996; Telonio and Smeesters, 2009; Thelen *et al.*, 1997).

1.2.1 Which postural perturbations have been experimentally studied?

Five different postural perturbations have been experimentally investigated using large postural perturbations at the threshold of balance recovery: lean releases, pulls, surface translations, slips and trips.

Lean release experiments

Lean releases are initiated by suddenly releasing participants from a static initial lean angle (Carbonneau and Smeesters, 2014; Cyr and Smeesters, 2007; 2009b; 2009c; Grabiner *et al.*, 2005; Hsiao-Wecksler and Robinovitch, 2007; Hsiao-Wecksler, 2008; Madigan and Lloyd, 2005a; 2005b; Madigan, 2006; Moglo and Smeesters, 2005; 2006; Owings *et al.*, 2000; Telonio and Smeesters, 2007; Telonio *et al.*, 2008; Telonio and Smeesters, 2008; 2009; Thelen *et al.*, 1997; 2000; Wojcik *et al.*, 1999; 2001). The initial lean angle is obtained by leaning participants forward, sideways or backwards from standing using a cable attached to a pelvic belt. The amplitude of the initial lean angle is controlled by adjusting the length of the lean cable. When the lean is released, the angular velocity (and to a lesser extent the angular position) of the participant increases, due solely to gravitational forces.

Pull experiments

Pulls can be suddenly initiated from a static standing or leaning position or while walking (Moglo and Smeesters, 2005; 2006). The pull force is applied with a cable attached to a pelvic belt using dropped weights or bungee cords under tension. For static initial positions the pull force can be applied forward, sideways or backwards, but while walking it has only be done for forward pulls at 50% swing. The amplitude of the pull force is controlled by increasing the number of weights or bungee cords. When the pull is applied, both the angular position and velocity of the participant increase.

Surface translation experiments

Surface translations are initiated by suddenly translating the surface the participant is statically standing or walking on (Feldman and Robinovitch, 2007; Hsiao and Robinovitch, 1998; Owings *et al.*, 2000; 2001; Pai, 1999; Pavol *et al.*, 2002b; 2004a; 2004b). It has never been attempted from a statically leaning initial position. The translation can be generated by springs under tension, a motor or a treadmill, and done forward, sideways or backwards. The amplitude of the translation may be controlled by the acceleration, velocity and/or displacement of the surface. When the translation is applied, both the angular position and velocity of the participant increase.

Slip experiments

Slips are initiated while walking and occur at double support, when the force applied by the front foot on the floor's surface suddenly exceeds the force provided by friction (Brady *et al.*, 2000; Cham and Redfern, 2001; Troy and Grabiner, 2006). The coefficient of friction of a section of the floor is altered by applying some contaminant (mineral oil, glycerol or K-Y jelly) or by using artificial ice. Slips usually result in backward and sometime sideways falls (Smeesters *et al.*, 2001b). Amplitude control is very difficult but could be done by controlling the coefficient of friction. When the slip is triggered, both the angular position and velocity of the participant increase.

Trip experiments

Trips are also initiated while walking but occur at single support, when the trajectory of the swing foot is suddenly stopped (Owings *et al.*, 2000; Pavol *et al.*, 1999a; 1999b; 2001; 2002a; Pijnappels *et al.*, 2001; 2004; 2005a; 2005b; 2005c; Smeesters *et al.*, 2001a). Swing can be interrupted by restraining a cable attached to one of the feet or using a suddenly appearing obstacle. Trips usually result in forward falls (Smeesters *et al.*, 2001b). Amplitude control is also difficult but can be done by controlling the length of time swing is interrupted (Smeesters *et al.*, 2001a). When the trip is triggered, both the angular position and velocity of the participant increase.

For safety reasons, all postural perturbations are conducted either on top of firm gymnasium mats or using a safety harness attached to an overhead rail by a cable. Although the participants usually know they are going to be perturbed, the postural perturbations are randomly triggered to maintain some effect of surprise. The amplitude of the postural perturbations is usually slowly incremented after each successful trial, until participants fail to recover balance twice at a given amplitude. Balance recovery is successful if participants use no more than the instructed number of step (a single step, two steps or no limit), do not touch the floor or the surface of the gymnasium mats with their hands, and/or do not support their body weight in the safety harness (less than 20 or 30% of body weight (Cyr and Smeesters, 2009a; Yang and Pai, 2011)). The threshold of balance recovery for each postural perturbation is thus the last successful trial at the maximum amplitude for that postural perturbation (maximum initial lean angle, pull force or surface translation velocity).

1.2.2 Can we compare experiments with different postural perturbations?

The great variety of postural perturbations used in the studies presented in the previous section make comparisons between studies difficult. In fact, although the same response initiation, execution and geometry variables are often measured, to our knowledge only three studies have attempted to compare results from different postural perturbations (Mansfield and Maki, 2009; Moglo and Smeesters, 2005; 2006). Being able to compare results across postural perturbations would help researchers make faster and broader conclusions about balance recovery abilities and thus make these results more readily available to clinicians for fall prevention and rehabilitation.

Mansfield and Maki (2009) compared medium pulls and surface translations while standing and walking in place in multiple directions and in both younger and older adults. They hypothesized that contradictions in age effects between studies using different postural perturbations could be due to:

- differences in the mechanical and sensory stimuli provoked by each perturbation;
- differences in the amplitude, timing (onset time and duration) and direction of each perturbation;
- differences in the capacity of the participant to predict perturbation amplitude, timing (onset time and duration) and direction;
- differences in the instructions given to the participant.

To avoid confounding factors, they thus varied both postural perturbations (type, amplitude, timing and duration) in an unpredictable manner and gave the same instructions to participants at each trial. Their results showed that, although age effects were usually less pronounced for pulls compared to surface translations, age effects were always in the same direction for both postural perturbations. However, their pulls were less destabilising (less center of mass motion prior to response initiation) than their surface translations and thus less effective in revealing age effects. Mansfield and Maki (2009) thus concluded that differences in the mechanical and sensory stimuli of each perturbation were less important than differences in perturbation amplitude and timing. They also emphasize the fact that, unfortunately, few studies provide sufficient details on their perturbation amplitude and timing, and that amplitudes can be difficult to compare (pull force versus surface translation acceleration).

Moglo and Smeesters (2005; 2006) compared large forward lean releases, lean releases with pulls and pulls while walking in both younger and older adults. Moreover, their studies were done at the threshold of balance recovery, which helped to resolve the difficulty in comparing postural perturbation amplitudes. Indeed, since the threshold of balance recovery is the maximum postural perturbation amplitude that participants can suddenly sustain and still successfully recover balance, the threshold of balance recovery in these studies was:

- the maximum initial lean angle that participants could be suddenly released from and still recover balance using a single step for lean releases with or without pulls;
- the maximum pull force that participants could suddenly sustain and still recover balance using a single step for pulls while walking.

Three important results came out of the first study (Moglo and Smeesters, 2005):

1. The three postural perturbations were definitely not the same. Not only were their initial angular positions and velocities different, but they also gave different results (Figure 1.2, thick dashed lines and filled symbols). Indeed, increasing pull force decreased the maximum lean angles and increasing walking velocity decreased the maximum pull forces.
2. Nevertheless, response initiation, execution and geometry variables for the threshold of balance recovery trials were nearly identical. Indeed, overall reaction time was significantly different between the five postural perturbations (1 lean release, 2 lean releases with pull and 2 pulls while walking), but none of the pairwise comparisons were significant. Moreover, weight transfer time, step time, step length and step velocity were not significantly different between the five postural perturbations.
3. In fact, their results were similar enough that they could be compared. Indeed, the angular positions and velocities at the end of reaction time for trials at the threshold of balance recovery formed a perturbation threshold line (Figure 1.2, thin solid and dashed lines and empty symbols). Moreover, this perturbation threshold line separated falls from recoveries,

regardless of the postural perturbation. Indeed, 98% of the angular positions and velocities at the end of reaction time of the failed balance recovery trials were above the perturbation threshold line (Figure 1.3, white area), while 97% of the angular positions and velocities at the end of reaction time of the successful balance recovery trials were below the perturbation threshold line (Figure 1.3, gray area).

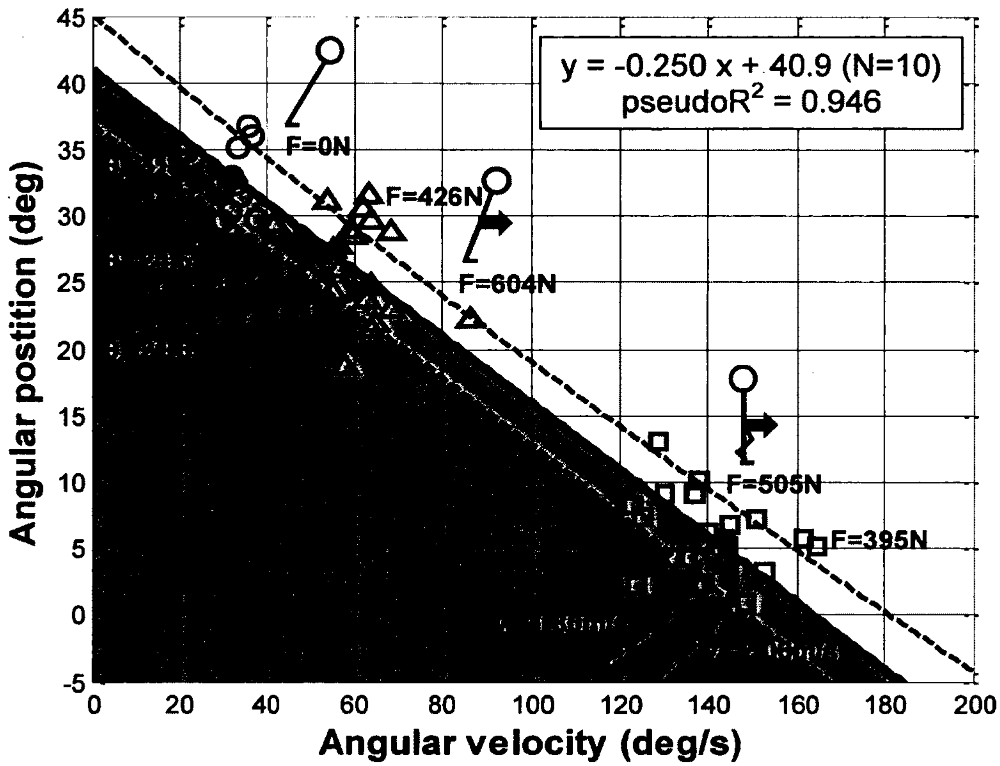

Figure 1.2: Perturbation threshold line for lean releases (circles), lean releases with pulls (triangles) and pulls while walking (squares) at the threshold of balance recovery (adapted with permission from Moglo and Smeesters, 2005).
The thick dashed lines ending in filled symbols were the average angular positions and velocities from onset of perturbation to onset of response. The thin solid and dashed lines were the perturbation threshold line (mean ± standard deviation) formed by the angular positions and velocities at the end of reaction time (empty symbols).

Finally, the second study (Moglo and Smeesters, 2006) showed that the perturbation threshold line declined with age, shifting down and to the left. Moglo and Smeesters (2005; 2006) have thus developed a dimensionless method to compare results from different postural perturbations and experimentally demonstrated that the choice of postural perturbation does not affect the threshold of balance recovery. That being said, their perturbation threshold line had a large gap in data points, between 80-120deg/s and 10-20deg, which could not be filled without increasing pull forces beyond safe levels (Figure 1.2 and Figure 1.3).

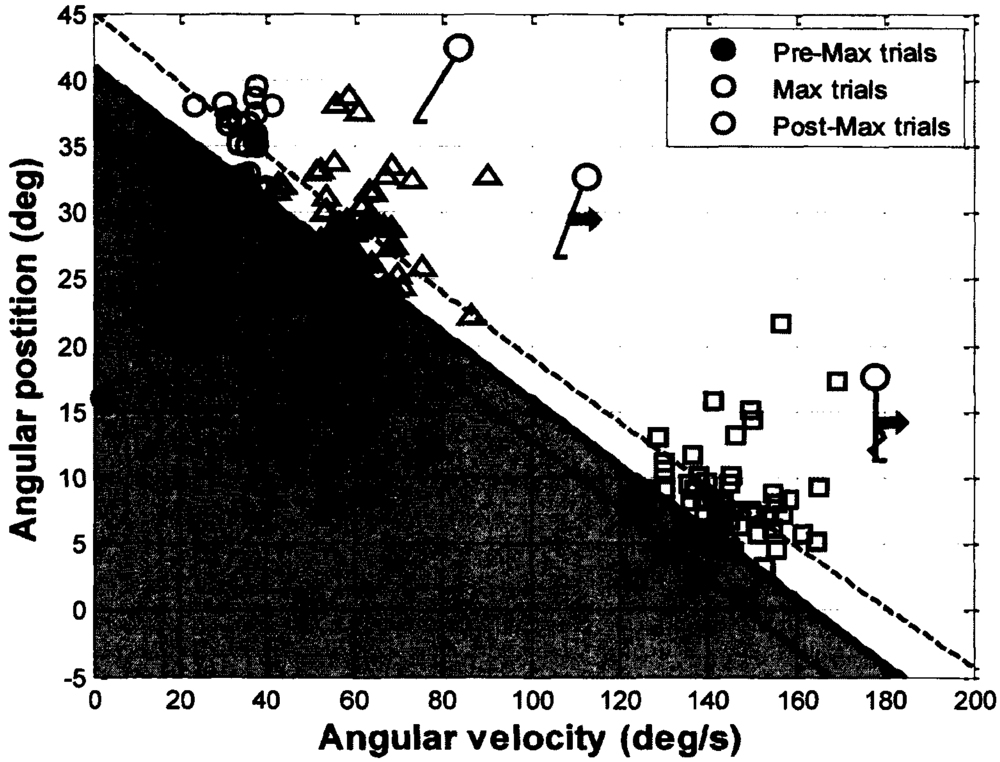

Figure 1.3: The perturbation threshold line (thick and thin full lines: mean ± standard deviation), obtained from the successful maximum lean angle (empty black circles), maximum lean angle with pull (empty black triangles) and maximum pull while walking (empty black squares) trials, separates falls from recoveries (reproduced with permission from Moglo and Smeesters, 2005).
The filled gray symbols were the angular position and velocity points at the end of reaction time for trials before the threshold of balance recovery where balance recovery was successful. The empty gray symbols were the angular position and velocity points at the end of reaction time for trials after the threshold of balance recovery where participants failed to recover balance.

1.3 The knowledge base on fall models

Unfortunately, balance recovery experiments are time consuming, expensive and can be dangerous. Participant recruitment is always a challenging, time consuming and sometimes expensive process, especially when recruiting frail older adults which can trigger additional concerns with ethics committees (Nelson *et al.*, 2002; Ory *et al.*, 2002; Verheggen *et al.*, 1998). Purchasing, maintaining and renewing laboratory equipment as well as running experiments is often expensive. More importantly, balance recovery experiments can be very demanding and fatiguing for older participants, which often lengthens experimental time. Finally, despite strict screening processes and even if appropriate safety measures are taken, balance recovery experiments can be dangerous for both younger and older participants, especially if large postural perturbations are used and avoiding a fall is not always possible. Therefore, it would be useful to be able to use a model instead of an experiment to theoretically predict if a given postural perturbation will lead to an unavoidable fall or if balance recovery is possible for a given individual participant. Indeed, theoretical models are usually faster and much less expensive than experiments. They are also not dangerous and never complain or get tired no matter how many times you run them.

This literature review will again primarily focus on models simulating large postural perturbations at the threshold of balance recovery, not models simulating small or medium postural perturbations (Hof *et al.*, 2005; Pai and Patton, 1997; Pai *et al.*, 2000; Park *et al.*, 2004; van der Kooij *et al.*, 2005) where only feet in place or stepping is necessary for balance recovery and falls never occur.

1.3.1 Which postural perturbations have been modelled?

All five postural perturbations covered in section 1.2.1 (lean releases, pulls, surface translations, slips and trips) have been modeled using large postural perturbations at the threshold of balance recovery. However, we must first mention the models developed by van den Kroonenberg *et al.* (1995) which to our knowledge were the first published models of falls from standing height. Their simple one-, two- and three-segment two-dimensional models were used to estimate impact forces in self-initiated sideways falls.

Lean release models

Six different studies have modeled lean releases. Hsiao and Robinovitch (1999) used a two-dimensional inverted pendulum model with a torsional spring as its pivoting stance ankle point and a linear spring as its step leg to simulate balance recovery by stepping from forward lean release to fall arrest. It predicted that, despite a desire to minimize recovery effort, successful balance recovery is governed by an interaction between step length, step time and leg strength. Thelen and Burd (2000) used a two-dimensional seven-segment model with thirty Hill-type musculo-tendon actuators driven by eighteen independent electromyography signals to simulate balance recovery by stepping from forward lean release to heel strike. It suggested that differences in stepping performance could come about from age-related changes in muscle strength and speed. Lo and Ashton-Miller (2008a) used a three-dimensional eleven-segment model with proportional-derivative feedback actuators to demonstrate how various pre-impact movement strategies (flexion of the lower extremities, ground contact with the side of the lower leg, axial rotation and using the arm to break the fall) can reduce impact forces in sideways falls from initial leans. Lo and Ashton-Miller (2008b) also used a two-dimensional seven-segment model with proportional-derivative feedback actuators to demonstrate how various joint control strategies (eccentric hip flexion prior to impact, arm retraction post impact) can reduce impact forces on the wrists in forward falls from initial leans. Smeesters (2009) showed promising preliminary results in the effectiveness of a two-dimensional inverted pendulum model, simply falling under gravity or with an additional pull force modelled as a step, in simulating the angular position and velocity of participants from onset of perturbation to onset of response for forward leans or leans with pulls, respectively. Finally, Aftab *et al.* (2012) used a two-dimensional inverted pendulum plus foot model with a closed loop linear model predictive controller to successfully predict step lengths for a complete multiple step balance recovery response from forward initial leans.

Pull models

To our knowledge, only one study modeled pulls at the threshold of balance recovery. Smeesters (2009) showed promising preliminary results in the effectiveness of a two dimensional inverted pendulum model, with a pull force modelled as a step, in simulating the angular position and velocity of participants from onset of perturbation to onset of response for forward pulls while walking.

Surface translation models

To our knowledge, only one study modeled surface translations for medium to large postural perturbations. Wu *et al.*, (2007) used two two-dimensional inverted pendulum plus foot models representing the stance and step legs and the work-energy principle to estimate the minimal step length needed for forward balance recovery with a single step. Although their results were consistent with medium surface translation results, they may not apply for surface translations at the threshold of balance recovery where the available stepping time is limited, since the work-energy principle approach cannot account for step time.

Slip models

To our knowledge, only one study modeled falls from slips. Smeesters *et al.* (2007) used the three-dimensional seventeen-segment and sixteen-joint articulated total body model to simulate passive falls following 30cm forward slips on a patch of floor with reduced friction coefficient (μ=0.03) so as to determine fall direction and impact locations for slow, normal and fast gait speeds.

Trip models

Five different studies have modeled forward trips. van den Bogert *et al.* (2002) used a two-dimensional inverted pendulum model to predict angular position of participants from onset of perturbation to response time (the time at which the tripped foot is lowered to the ground so as to allow stepping with the other foot). It predicted that faster response time was more important than slower walking velocity for successful recovery. Forner Cordero *et al.* (2004) used a two-dimensional three-segment model, an inverted pendulum trunk connected at the hip to two leg segments of variable length, during the double support phase of balance recovery following a trip from heel strike to fall arrest. It described the hip torques necessary to control the trunk as a function of hip trajectory, ground reaction forces and their application points. Smeesters *et al.* (2007) used the three-dimensional seventeen-segment and sixteen-joint articulated total body model to simulate passive falls following trips due to contact with an obstacle so as to determine fall direction and impact locations for slow, normal and fast gait speeds. Roos *et al.* (2010) used a two-dimensional inverted pendulum model with a torsional spring as its pivoting stance ankle point and a linear spring as its step leg to simulate balance recovery by stepping from trip onset to fall arrest. It demonstrated that, when perturbed later in swing, a larger step and higher limb forces were required for successful recovery. Shiratori *et al.* (2009) used a three-dimensional seventeen-segment and sixteen-joint model and finite state machines to control a human simulation of balance recovery from a trip due to contact with an obstacle in an interactive environment.

1.3.2 Could we use a single model for all postural perturbations?

The literature review in the previous section has revealed that various forms of two-dimensional inverted pendulum models have been successfully used for medium to large postural perturbations in three of the six lean release models, in the single pull model, in the single surface translation model and in three of the five trip models. Is it possible that a single inverted pendulum model could be used to model all five postural perturbations? Unfortunately, the specific aims and output variables examined with the inverted pendulum models of each of the previous studies were not capable of answering this question. However, the dimensionless perturbation threshold line method to experimentally compare results from different postural perturbations from Moglo and Smeesters (2005; 2006) and the preliminary results from Smeesters (2009) on the effectiveness of the same two dimensional inverted pendulum model in simulating leans, leans with pulls and pulls while walking as well as the perturbation threshold line hint that it may indeed be possible. In fact, as the stability boundary method by Pai *et al.* (2000) obtained using an inverted pendulum model established a threshold in center of mass position versus velocity phase space between feet in place and stepping balance recovery strategies, the perturbation threshold line method by Moglo and Smeesters (2005; 2006) obtained using experiments established a threshold in participant angular position versus velocity phase space between recoveries and falls. A single inverted pendulum model would thus greatly reduce the need for time consuming, expensive and dangerous experiments, especially if it can predict if a given postural perturbation will lead to an unavoidable fall or if balance recovery is possible. For example, it could simulate future experiments to determine the best range and levels of postural perturbation amplitudes to insure a good distribution of results and determine the specifications of the necessary equipment. It could also simulate experiments in frail older adults that are unable to participate in experiments.

1.4 Research project objectives

In an effort to pursue the work by Moglo and Smeesters (2005; 2006) and Smeesters (2009) on the dimensionless perturbation threshold line method, the overall long term objective of our laboratory is to determine if balance recovery is possible or if a fall is unavoidable, for any perturbation applied on an individual by both experimental and theoretical means. To do so, we first had to determine what experimental postural perturbations were currently available to us amongst the five postural perturbations reviewed in section 1.2.1: lean releases, pulls, surface translations, slips and trips.

1.4.1 Which experimental postural perturbations were available?

In the Biomechanics of Movement Laboratory of Professor Cécile Smeesters at the Research Center on Aging at the Université de Sherbrooke in Sherbrooke QC, the equipment for lean releases was available. The equipment previously used by Moglo and Smeesters (2005; 2006) for pulls was no longer available as pursuing this particular postural perturbation was not possible without increasing pull forces beyond safe levels (section 1.2.2). Finally, the equipment for surface translations, slips or trips had never been available in this laboratory.

In the Injury Prevention and Mobility Laboratory of Professor Stephen N. Robinovitch from the Department of Biomedical Physiology and Kinesiology at Simon Fraser University in Burnaby BC, the equipment for lean releases and surface translations was available. Furthermore, the equipment for pulls, slips and trips had never been available in this laboratory. More importantly, Professor Robinovitch had agreed to collaborate with us following some successful preliminary trials on the surface translation equipment during the 2008-2009 sabbatical of Professor Smeesters in his laboratory. The experimental part of this master's thesis thus took place in his laboratory at Simon Fraser University.

The overall objective of this master's thesis was thus to determine if balance recovery is possible or if a fall is unavoidable, for lean releases and surface translations at the threshold of balance recovery by both experimental and theoretical means. In particular, we hoped that the addition of the surface translations might fill in the gap in data points between 80-120deg/s and 10-20deg in the perturbation threshold line previously obtained by Moglo and Smeesters (2005) using lean releases, lean releases with pulls and pulls while walking (section 1.2.2).

1.4.2 Specific aims and hypotheses

This master's thesis will thus contain an experimental publication (Chapter 2) and a theoretical publication (Chapter 3). The specific aims and hypotheses of each publication were as follows:

- *Experimental specific aim:* To determine the maximum forward initial lean angle and the maximum backward surface translation velocity from which younger adults could be suddenly released or pulled, respectively, and still recover balance using a single step (Cyr and Smeesters, 2007; 2009c).
- *Experimental hypothesis 1:* The angular positions and velocities at the end of reaction time for lean release and surface translation trials at the threshold of balance recovery would form a perturbation threshold line similar to the one obtained by Moglo and Smeesters (2005) using lean releases, lean releases with pulls and pulls while walking.
- *Experimental hypothesis 2:* Response initiation, execution and geometry variables for the maximum lean angle and maximum translation velocity trials would not be significantly different between the two postural perturbations.
- *Theoretical specific aim:* To determine if a two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid could simulate the angular position and velocity of participants from onset of perturbation to onset of response for both lean releases and surface translations.
- *Theoretical hypothesis:* The inverted pendulum on a skid model would accurately simulate the angular position and velocity of participants from onset of perturbation to onset of response for both the lean releases and surface translations.

A general discussion of these two publications (Chapter 4) will follow as well as a conclusion on this master's thesis (Chapter 5).

1.5 References

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CHAPTER 2 EXPERIMENTAL PUBLICATION

2.1 Preface

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Date of submission: January 24 2014

Journal: Journal of Biomechanics

English title: Comparison of the kinematics of the threshold of balance recovery of two postural perturbations: lean release and surface translation

French title: Comparaison de la cinématique de la limite du rétablissement de l'équilibre de deux perturbations posturales : relâchement d'une inclinaison et translation de surface

Contribution to the document:

This article contributes to this master's thesis by answering the experimental specific aim, which is to determine the maximum forward initial lean angle and the maximum backward surface translation velocity from which younger adults could be suddenly released or pulled, respectively, and still recover balance using a single step.

French abstract:

La grande variété de perturbations posturales utilisées dans les études expérimentales rend les comparaisons entre les études et les généralisations sur les capacités à rétablir l'équilibre difficile. En effet, seulement trois études ont tenté de comparer les résultats de différentes perturbations posturales. Pour poursuivre les travaux de Moglo et Smeesters

(2005; 2006) sur la méthode adimensionnelle de ligne de perturbation limite, nous avons déterminé l'angle maximum d'inclinaison initiale vers l'avant et la vitesse maximum de translation de surface vers l'arrière desquels 12 jeunes adultes pouvaient être soudainement relâchés ou tirés, respectivement, et tout de même rétablir leur équilibre en utilisant un seul pas. Les résultats ont démontré des angles maximum d'inclinaison de 27.3±4.8deg et des vitesses maximum de translation de 2.42±0.36m/s (N=12). Aux angles d'inclinaison ou vitesses de translation maximum, les deux perturbations posturales n'avaient pas d'effet significatif sur l'initiation de la réponse, mais affectaient la plupart des variables d'exécution et de géométrie de la réponse. Néanmoins, les positions et vitesses angulaires à la fin du temps de réaction pour ces essais à la limite du rétablissement de l'équilibre formaient une ligne de perturbation limite qui était très similaire à celle obtenue par Moglo et Smeesters (2005). De plus, la ligne de perturbation limite était très efficace pour séparer les chutes (97%) des rétablissements (96%), quelle que soit la perturbation posturale. La méthode adimensionnelle de ligne de perturbation limite a maintenant été établie expérimentalement pour les relâchements d'inclinaison, relâchements d'inclinaison avec tirages à la taille, tirages à la taille en marchant et translations de surface, fournissant ainsi des preuves additionnelles que le choix de la perturbation posturale n'affecte pas la limite du rétablissement de l'équilibre. Cela devrait donc aider les chercheurs à faire des conclusions plus rapides et plus générales sur les capacités à rétablir l'équilibre.

Note: Following the corrections requested by the members of the jury, the content of this article differs from the one submitted.

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Comparison of the Kinematics of the Threshold of Balance Recovery of Two Postural Perturbations: Lean Release and Surface Translation

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2.2 Abstract

The great variety of postural perturbations used in experimental studies make comparisons between studies and generalizations about balance recovery abilities difficult. In fact, only three studies have attempted to compare results from different postural perturbations. To pursue the work by Moglo and Smeesters (2005; 2006) on the dimensionless perturbation threshold line method, we determined the maximum forward initial lean angle and the maximum backward surface translation velocity from which 12 younger adults could be suddenly released or pulled, respectively, and still recover balance using a single step. Results showed maximum lean angles of 27.3±4.8deg and maximum translation velocities of 2.42±0.36m/s (N=12). At the maximum lean angles or maximum translation velocities, the two postural perturbations did not have a significant effect on response initiation, but did affect most response execution and response geometry variables. Nevertheless, the angular positions and velocities at the end of reaction time for these trials at the threshold of balance recovery formed a perturbation threshold line that was very similar to the one obtained by Moglo and Smeesters (2005). Furthermore, the perturbation threshold line was very efficient in separating falls (97%) from recoveries (96%), regardless of the postural perturbation. The dimensionless perturbation threshold line method has now been experimentally established for lean releases, lean releases with waist pulls, waist pulls while walking and surface translations, thus providing further evidence that the choice of postural perturbation does not affect the threshold of balance recovery. It should therefore help researchers make faster and broader conclusions about balance recovery abilities.

Abstract Word Count: 250 / 250 words

2.3 Introduction

Falls occur without warning and it is ethically and logistically very difficult to record these real life events with accurate instruments to quantify and characterize falls. For example, some investigators have used video capture in long term care facilities to identify the circumstances of falls but actually capturing falls is rare and even when the recording is usable data analysis is limited, not precise, very tedious and complex (Robinovitch *et al.*, 2013; Yang *et al.*, 2013). Although experiments are not totally representative of real life falls, the laboratory offers better control of the field of view of cameras, a greater number of measurements available and better accuracy of these measurements. Therefore, fall experiments in the laboratory are essential.

Five different postural perturbations have been experimentally investigated using large postural perturbations at the threshold of balance recovery, where balance recovery and avoiding a fall is not always possible: lean releases, waist pulls, surface translations, slips and trips. Lean releases were initiated by suddenly releasing participants from a forward, sideways or backwards initial lean angle (Carbonneau and Smeesters, 2014; Cyr and Smeesters, 2007; 2009a; 2009b; Grabiner *et al.*, 2005; Hsiao-Wecksler and Robinovitch, 2007; Hsiao-Wecksler, 2008; Madigan and Lloyd, 2005a; 2005b; Madigan, 2006; Moglo and Smeesters, 2005; 2006; Owings *et al.*, 2000; Telonio and Smeesters, 2007; Telonio *et al.*, 2008; Telonio and Smeesters, 2008; 2009; Thelen *et al.*, 1997; 2000; Wojcik *et al.*, 1999; 2001). Forward waist pulls were suddenly initiated using dropped weights and bungee cords from standing or leaning positions or at 50% swing while walking (Moglo and Smeesters, 2005; 2006). Surface translations were initiated by suddenly translating forward, sideways or backwards the surface the participant was standing or walking on using springs, a motor or a treadmill (Feldman and Robinovitch, 2007; Hsiao and Robinovitch, 1998; Owings *et al.*, 2000; 2001; Pai, 1999; Pavol *et al.*, 2002b; 2004a; 2004b). Slips were initiated while walking using contaminants or artificial ice and occurred at double support, when the force applied by the front foot on the floor's surface suddenly exceeded the force provided by friction (Brady *et al.*, 2000; Cham and Redfern, 2001; Troy and Grabiner, 2006). Trips were also initiated while walking but occurred at single support, when the trajectory of the swing foot was suddenly stopped using a cable attached to the foot or an obstacle (Owings *et al.*, 2000; Pavol *et al.*, 1999a; 1999b; 2001; 2002a; Pijnappels *et al.*, 2001; 2004; 2005a; 2005b; 2005c; Smeesters *et al.*, 2001).

However, the great variety of postural perturbations used make comparisons between studies and generalizations about balance recovery abilities difficult. In fact, although the same response initiation, execution and geometry variables are often measured, to our knowledge only three studies have attempted to compare results from different postural perturbations (Mansfield and Maki, 2009; Moglo and Smeesters, 2005; 2006).

Mansfield and Maki (2009) compared medium waist pulls and surface translations while standing and walking in place in multiple directions and in both younger and older adults. Their results showed that, although age effects were usually less pronounced for waist pulls compared to surface translations, age effects were always in the same direction for both postural perturbations. However, their waist pulls were less destabilising than their surface translations. Mansfield and Maki (2009) thus concluded that differences in the mechanical and sensory stimuli of each perturbation were less important than differences in perturbation amplitude and timing. Unfortunately, amplitudes can be difficult to compare (waist pull force versus surface translation acceleration).

Moglo and Smeesters (2005; 2006) compared large forward lean releases, lean releases with waist pulls and waist pulls while walking in both younger and older adults. Moreover, their studies were done at the threshold of balance recovery, which helped resolve the difficulty in comparing postural perturbation amplitudes. Indeed, the threshold of balance recovery in these studies were the maximum initial lean angle and the maximum waist pull force that participants could be suddenly released from or could suddenly sustain and still recover balance using a single step for lean releases with or without waist pulls and waist pulls while walking, respectively. Their results showed that, the three postural perturbations were definitely not the same and gave different results: increasing waist pull force decreased the maximum lean angles and increasing walking velocity decreased the maximum waist pull forces (Figure 2.1 top, thick dashed lines and filled symbols). Nevertheless, response initiation (reaction time), execution (weight transfer time, step time and step velocity) and geometry variables (step length) for the threshold trials were nearly identical for all postural perturbations. Furthermore, from onset of perturbation to onset of response, their results were similar enough that they could be compared. Indeed, the angular positions and velocities at the end of reaction time of the threshold trials formed a perturbation threshold line (Figure 2.1, thin solid and dashed lines and empty black symbols) separating falls (Figure 2.1 bottom, white area and empty gray symbols) from recoveries (Figure 2.1 bottom, gray area and filled gray symbols), regardless of the postural perturbation. Moglo and Smeesters (2005; 2006) have thus developed a dimensionless method to compare results from different postural perturbations and experimentally demonstrated that the choice of postural perturbation does not affect the threshold of balance recovery.

In an effort to pursue the work by Moglo and Smeesters (2005; 2006) on the perturbation threshold line method, the purpose of this study was to compare the kinematics of lean releases and surface translations at the threshold of balance recovery in younger adults. To do so we determine the maximum forward initial lean angle and the maximum backward surface translation velocity from which younger adults could be suddenly released or pulled, respectively, and still recover balance using a single step (Cyr and Smeesters, 2007; 2009b).

2.4 Methods

2.4.1 Participants

Balance recoveries from both lean releases and surface translations were performed by 12 healthy younger adults, six women (mean±SD=25.0±3.0yrs, range=22-30yrs; 1.53±0.09m; 54.7±13.4kg) and six men (27.5±3.5yrs, 23-32yrs; 1.68±0.08m; 77.3±12.6kg). Ethics approval was obtained from both institutions, Université de Sherbrooke and Simon Fraser University. Participants with musculoskeletal problems were excluded.

2.4.2 Experimental procedure

Both postural perturbations were conducted on top of a firm gymnasium mat (8ft x 4ft x 1ft). All participants wore fitted shorts, a sleeveless t-shirt, sneakers and a helmet. A safety harness attached to an overhead rail by a cable, whose length was adjusted to prevent participants from touching the gymnasium mat with their hands, was also used. A 10min rest period was used between the two postural perturbations to reduce fatigue and the order was randomised for each participant by gender to balance out any learning effect.

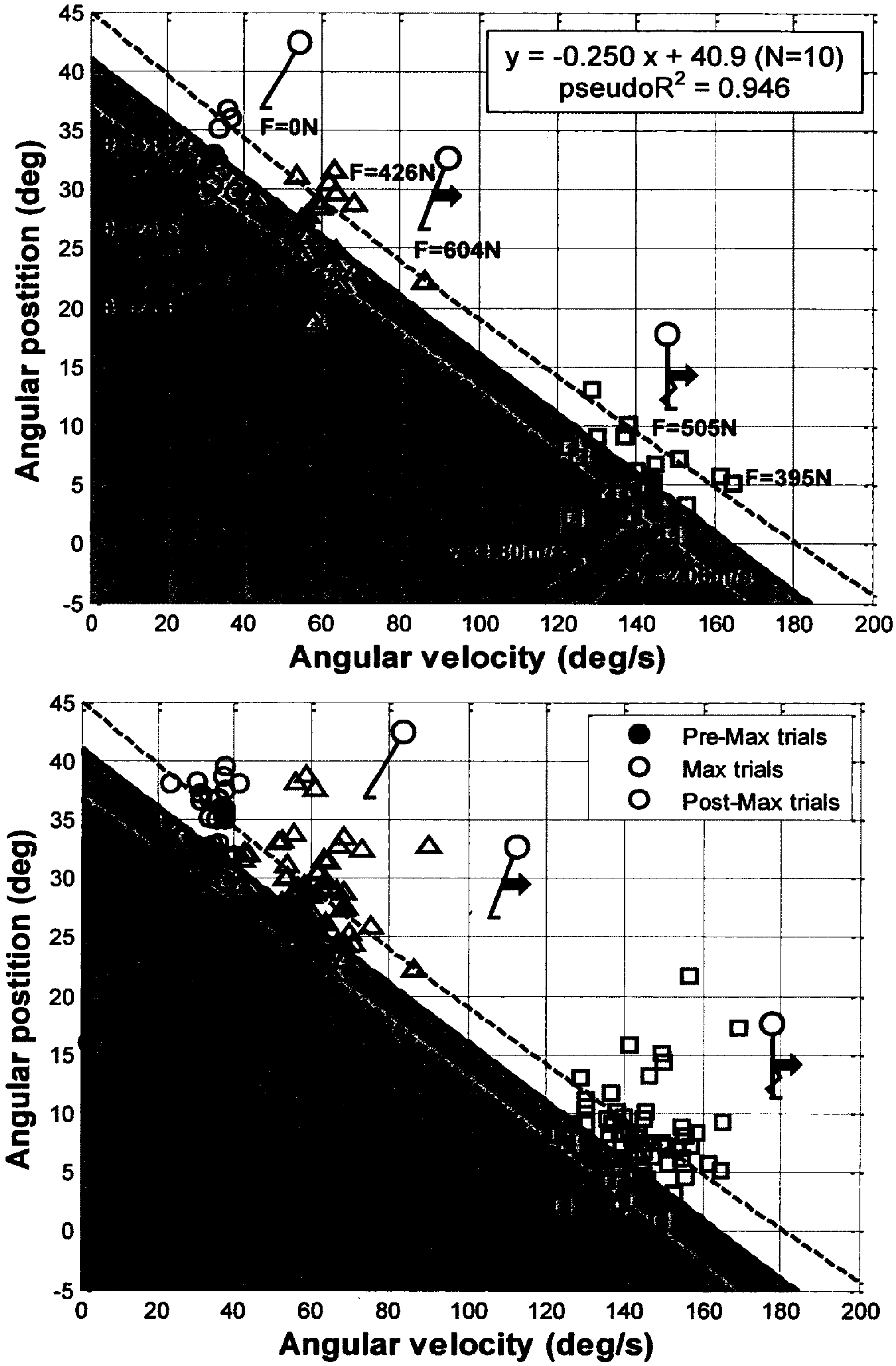

Figure 2.1: Perturbation threshold line for lean releases (circles), lean releases with waist pulls (triangles) and waist pulls while walking (squares) at the threshold of balance recovery separates falls from recoveries (adapted with permission from Moglo and Smeesters, 2005).

Top graph: The thick dashed lines ending in filled symbols were the average angular positions and velocities from onset of perturbation to onset of response. The thin solid and dashed lines were the perturbation threshold line (mean ± standard deviation) formed by the angular positions and velocities at the end of reaction time for the threshold trials (empty symbols). Bottom graph: The empty black symbols were the angular position and velocity points at the end of reaction time for the successful maximum lean angle, maximum lean angle with waist pull and maximum waist pull while walking trials which formed the perturbation threshold line (thin solid and dashed lines: mean ± standard deviation). The filled gray symbols were the angular position and velocity points at the end of reaction time for trials before the threshold of balance recovery where balance recovery was successful. The empty gray symbols were the angular position and velocity points at the end of reaction time for trials after the threshold of balance recovery where participants failed to recover balance.

Lean releases

For lean releases (Figure 2.2a, (Cyr and Smeesters, 2009b)), we determined the maximum forward initial lean angle from which each participant could be suddenly released and still recover balance using a single step. Participants were initially leaned forward from standing using a cable attached to a pelvic belt. After a random delay, the lean cable was suddenly released resulting in a forward loss of balance from which participants had to recover using a single step. The amplitude of this perturbation, the initial lean angle, was controlled by adjusting the length of the lean cable. It started at 10deg, was increased in 5deg and ultimately 2.5deg increments after each successful trial, until participants failed to recover balance twice at a given initial lean angle. The threshold of balance recovery for lean releases was thus the last successful trial at the maximum initial lean angle.

Surface translations

For surface translations (Figure 2.2b, (Feldman and Robinovitch, 2007)), we determined the maximum backward surface translation velocity from which each participant could be suddenly pulled and still recover balance using a single step. Participants initially stood on a rubber sheet. After a random delay, the rubber sheet was suddenly pulled backward by a linear motor (T4D, Trilogy System Corporation, Webster TX) resulting in a forward loss of balance from which participants had to recover using a single step. The amplitude of this perturbation, the surface translation velocity, was controlled by adjusting the velocity of the linear motor while keeping its displacement and acceleration constant at 700mm and 25m/s^2, respectively. It started at 1m/s and was increased in 0.25m/s increments after each successful trial, until participants failed to recover balance twice at a given surface translation velocity. The threshold of balance recovery for the surface translations was thus the last successful trial at the maximum surface translation velocity.

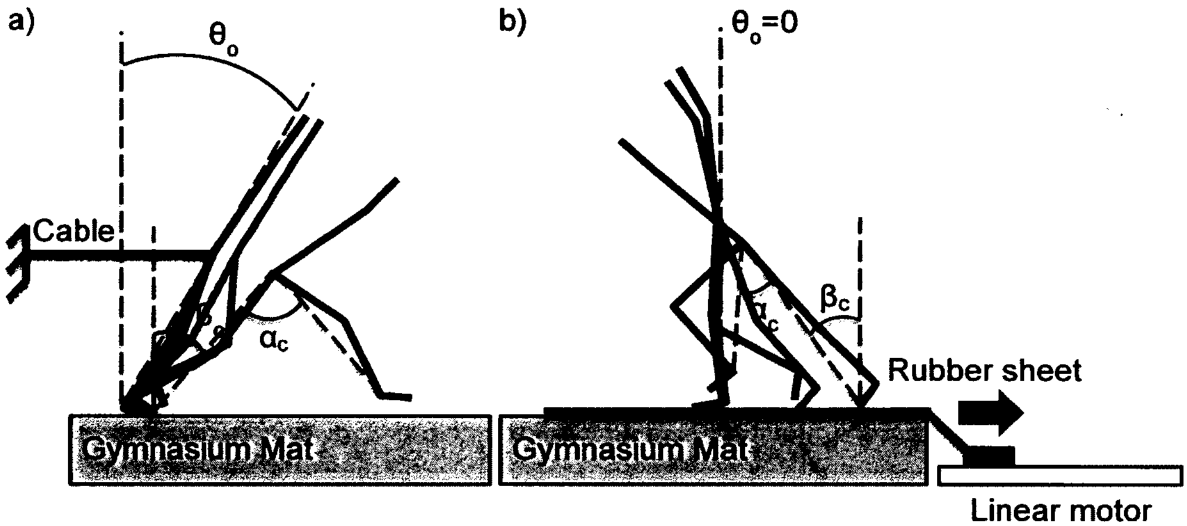

Figure 2.2 : Experimental setup for the lean releases (a) and surface translations (b) at the threshold of balance recovery, i.e., at the maximum initial lean angle (θ_{max}) and the maximum surface translation velocity (V_{max}), respectively.
Typical sagittal plane diagrams of the marker positions are shown at onset of perturbation (blue), toe off (green) and heel strike (red). Illustrated markers are the midpoints of the medial and lateral metatarsals and malleoli of the step and stance feet, the femoral epicondyles of the step and stance leg, the midpoints of the greater trochanters, acromions and temples. Note that the initial lean angle $\theta_o \neq 0$ for lean releases and $\theta_o=0$ for surface translations, but that both postural perturbations had the initial lean velocity $\omega_o=0$ and resulted in forward losses of balance. Finally, the stepping angle (α_c) and modified lean angle (β_c) at stepping foot contact are also shown.

For both postural perturbations, balance recovery was successful if participants used no more than one step (as instructed), did not touch the surface of the gymnasium mat with their hands, and did not support their body weight in the safety harness (cable remained slack).

2.4.3 Measuring instruments and variables

Kinematic data, consisting of the three-dimensional positions of 16 passive markers on the participant (Figure 2.2) and 2 passive markers on the linear motor and rubber sheet, were recorded by 8 optoelectronic sensors (Motion Analysis Inc., Santa Rosa CA) at 100Hz. Kinetic data, consisting of ground reaction forces and lean cable load (Figure 2.3), were recorded by 2 force plates (FP 3060-15 and FP 6090-15, Bertec corporation, Colombus OH) and a single degree of freedom load cell (MLP-500, Transducer Techniques, Temecula CA), respectively, at 1000Hz. Both data were synchronised and processed using Matlab (Mathworks, Natick MA). Marker positions, ground reaction forces and lean cable loads were filtered using zero-phase-shift 4^{th} order Butterworth filters at cutoff frequencies determined by residual analysis of 13Hz, 60Hz and 75Hz, respectively (Winter, 2005). Finally, velocities and accelerations were obtained from positions by first and second order centered finite differences on two and three points, respectively.

For both postural perturbations, the main variables were the angular position (θ) and velocity (ω). The angular position was measured as the sagittal plane angle between the vertical and the line connecting the midpoints of the medial and lateral malleoli of the stance foot and the two greater trochanters (Cyr and Smeesters, 2009b). At the onset of perturbation (OP) the angular position was the initial lean angle (θ_o, Figure 2.2) and, more importantly, the maximum initial lean angle (θ_{max}) for lean releases at the threshold of balance recovery. For surface translations, the anterior-posterior velocity of the marker on the linear motor (V) was also measured (Figure 2.3) and, more importantly, the maximum surface translation velocity (V_{max}) at the threshold of balance recovery.

Response initiation was measured by reaction time (RT), the time difference between onset of response (OR) and onset of perturbation (Figure 2.3, (Cyr and Smeesters, 2009b)). Onset of perturbation occurred when the lean cable load started decreasing or the surface translation velocity started increasing. Onset of response occurred when the vertical ground reaction force started increasing (at inflection point), ignoring the artefact at the onset of surface translation.

Response execution was measured by three variables (Cyr and Smeesters, 2009b). Weight transfer time (WTT) was the time difference between toe off (TO) and onset of response. Step time (ST) was the time difference between heel strike (HS) and toe off. Step velocity (SV) was step length (SL) divided by step time. Toe off occurred when the anterior-posterior acceleration of the midpoint of the medial and lateral metatarsals of the stepping foot reached a local maximum (lean releases) or minimum (surface translations). Heel strike occurred when the vertical ground reaction force started increasing again.

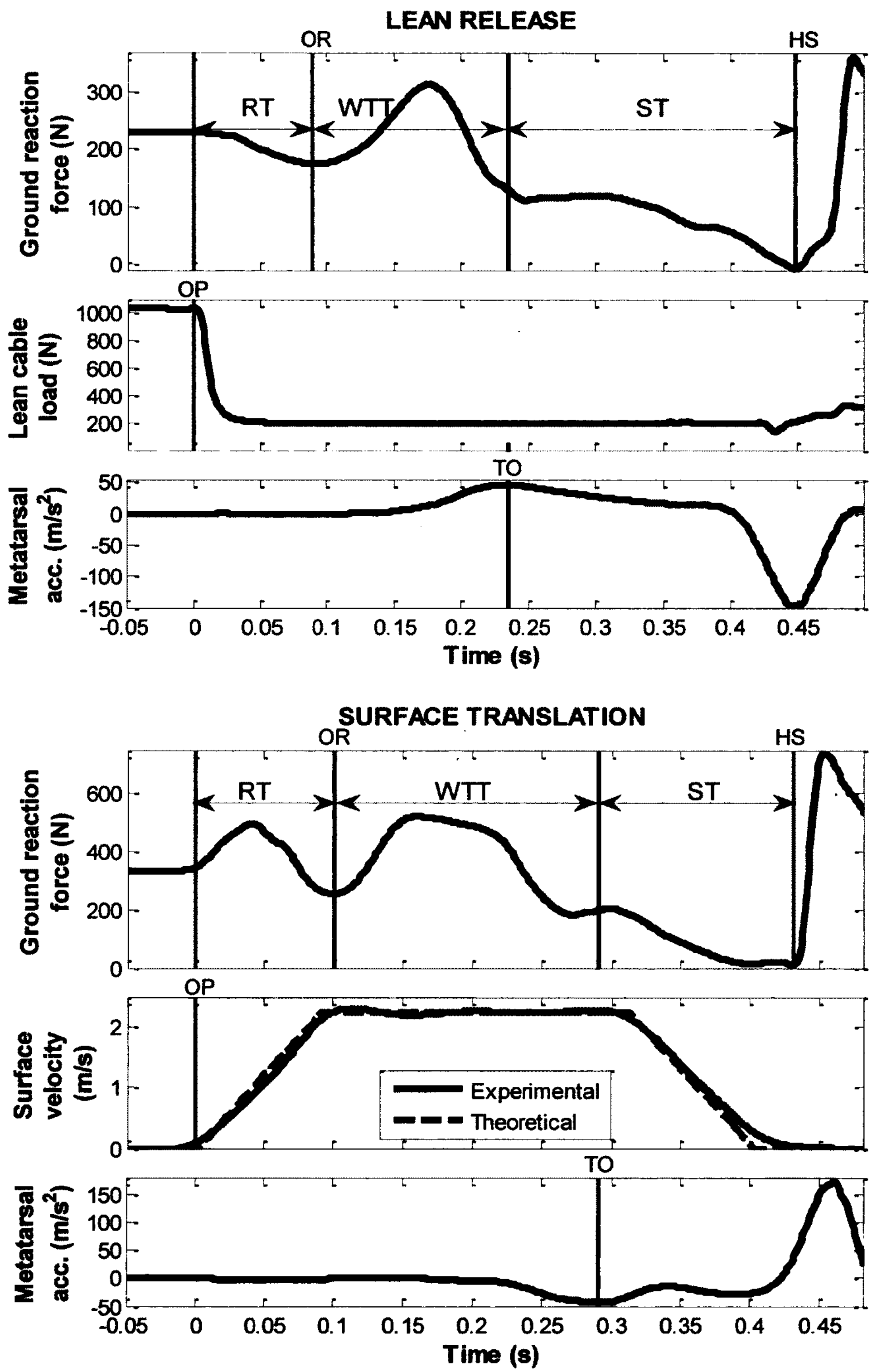

Figure 2.3: Time histories for lean releases (top three graphs) and surface translations (bottom three graphs) for a typical participant at the threshold of balance recovery, i.e., at the maximum initial lean angle (θ_{max}) and the maximum surface translation velocity (V_{max}), respectively.

Each triplet of graphs show: vertical ground reaction force (top), the force on the lean cable or the surface translation velocity (middle), and the anterior-posterior metatarsal acceleration of the stepping foot (bottom). Also shown are reaction time (RT) from onset of perturbation (OP) to onset of response (OR), weight transfer time (WTT) from OR to toe off (TO), and step time (ST) from TO to heel strike (HS). For surface translations, note that the initial increase in ground reaction force at the onset of perturbation is an artefact caused by the rubber sheet pushing down on the gymnasium mat as it is suddenly pulled backward. Note also that the experimental surface translation velocity, as measured by the marker on the linear motor, was a very good match to the theoretical surface translation velocity programmed into the linear motor. Finally, TO occurred when the anterior-posterior metatarsal acceleration reached a local extremum, maximum for lean releases and minimum for surface translations, the reversal due to the fact that the two perturbations faced opposite directions in the experimental setup.

Finally, response geometry was measured by four variables. Step length was the anterior-posterior displacement of the midpoint of the medial and lateral malleolus of the stepping foot from liftoff to touchdown (Cyr and Smeesters, 2009b). The stepping angle (α_c), modified lean angle (β_c) and the angular ratio (AR=α_c/β_c) at stepping foot contact were also calculated (Figure 2.2, (Hsiao and Robinovitch, 2001)). The sagittal plane angle formed by the midpoints of the medial and lateral metatarsals of the stance foot, the two greater trochanters and the medial and lateral malleoli of the stepping foot at heel strike defined the stepping angle. The sagittal plane angle between the vertical and the line connecting the midpoints of the medial and lateral metatarsals of the stance foot and the two greater trochanters at heel strike defined the modified lean angle.

2.4.4 Data analysis

Data were analysed using SPSS (SPSS Inc., Chicago IL) and $p \leq 0.05$ were significant. Since t-tests confirmed that gender did not affect maximum lean angles for lean releases ($p=0.770$) and maximum translation velocities for surface translations ($p=0.252$), gender effects were not considered. Simple paired t-tests were thus used to determine the effect of the two postural perturbations on each of the kinematic variables at the maximum lean angles or translation velocities. Finally, a linear regression was also used to establish the relationship between the angular positions and velocities at the end of reaction time for trials at the threshold of balance recovery.

2.5 Results

For surface translations, 4 participants (1 women and 3 men) never failed to recover balance even at the greatest surface translation velocity (V=2.75m/s) achievable with the linear motor. However, maximum lean angles for lean releases were not significantly different between surface translation fallers and non-fallers (p=0.903). The effect of the two postural perturbations was thus evaluated twice (Table 2.1), first with only the fallers (N=8) and then with both the fallers and non-fallers (N=12), setting the maximum translation velocity V_{max}=2.75m/s for the 4 non-fallers.

2.5.1 Postural perturbation effects for fallers only (N=8)

Considering only fallers, the threshold of balance recovery were maximum lean angles θ_{max}=27.4±5.7deg for lean releases and maximum translation velocities V_{max}=2.25±0.33m/s for surface translations. At the maximum lean angles or translation velocities, the two postural perturbations did not have a significant effect on response initiation, but did affect most response execution and response geometry variables. Specifically, reaction times were not affected by the two postural perturbations (p=0.179). While weight transfer times were not affected by the two postural perturbations (p=0.084), step times were 45ms shorter (p=0.004) and step velocities were 0.46m/s slower (p=0.038) for surface translations. Finally, while modified lean angles (p=0.818) were not affected by the two postural perturbations, step lengths were 269mm shorter (p<0.001), step angles were 23.5deg smaller (p<0.001) and angular ratios were 0.56 smaller (p<0.001) for surface translations.

2.5.2 Postural perturbation effects for fallers and non-fallers (N=12)

Considering both fallers and non-fallers, the threshold of balance recovery were maximum lean angles θ_{max}=27.3±4.8deg for lean releases and maximum translation velocities V_{max}=2.42±0.36m/s for surface translations. Results for the effect of the two postural perturbations on each of the kinematic variables at the maximum lean angles or translation velocities were very similar to those obtained with only fallers. The only notable exception was weight transfer times which were 27ms longer for surface translations (p=0.010).

2.5.3 Perturbation threshold line

Considering only fallers, the linear regression between the angular positions and velocities at the end of reaction time for trials at the threshold of balance recovery (Figure 2.4) was very similar to the one obtained by Moglo and Smeesters (2005). Moreover, the angular position and velocity points at the end of reaction time for the maximum lean angle and the greatest translation velocity trials of 3 of the 4 non-fallers (75%) were within one standard deviation. Finally, as the initial lean angle or surface translation velocity increased, the angular position and velocity points at the end of reaction time got closer to the perturbation threshold line (Figure 2.5). Nevertheless, 96% of the angular position and velocity points at the end of reaction time for trials before the threshold of balance recovery were below the mean plus one standard deviation. Furthermore, 97% of the angular position and velocity points at the end of reaction time for trials after the threshold of balance recovery were above the mean minus one standard deviation.

2.6 Discussion

While the maximum forward initial lean angles of θ_{max}=27.3±4.8deg for younger adults was comparable to those obtained by other studies (Cyr and Smeesters, 2009b; Hsiao-Wecksler and Robinovitch, 2007; Madigan and Lloyd, 2005a; Wojcik *et al.*, 1999), this is the first determination of the maximum backward surface translation velocities of Vmax=2.42±0.36m/s for younger adults (Table 2.1).

As Moglo and Smeesters (2005; 2006) had shown previously, despite differences in results for the various postural perturbations at the threshold of balance recovery, the results were similar enough that they could be compared from onset of perturbation to onset of response. Indeed, while both this study and the ones by Moglo and Smeesters (2005; 2006) had nearly identical response initiation variables regardless of the postural perturbation, Moglo and Smeesters (2005; 2006) had nearly identical response execution and geometry variables for maximum lean angle and maximum pull force trials but this study had significantly different response execution and response geometry variables for maximum lean angle and maximum translation velocity trials. Nevertheless, the angular positions and velocities at the end of reaction time for these trials at the threshold of balance recovery formed perturbation threshold lines that were very similar between the two studies. In fact, the slight differences between the two perturbation threshold lines were easily explained: while the efficiency of the lean release equipment was better in Moglo and Smeesters (2005), the efficiency of the surface translation (compared to waist pull) equipment was better for this study, which is why it was easier for subject to perform better. Finally, in both studies, the perturbation threshold line was very efficient in separating falls (97-98%) from recoveries (96-97%), regardless of the postural perturbation (Figure 2.1 and Figure 2.5).

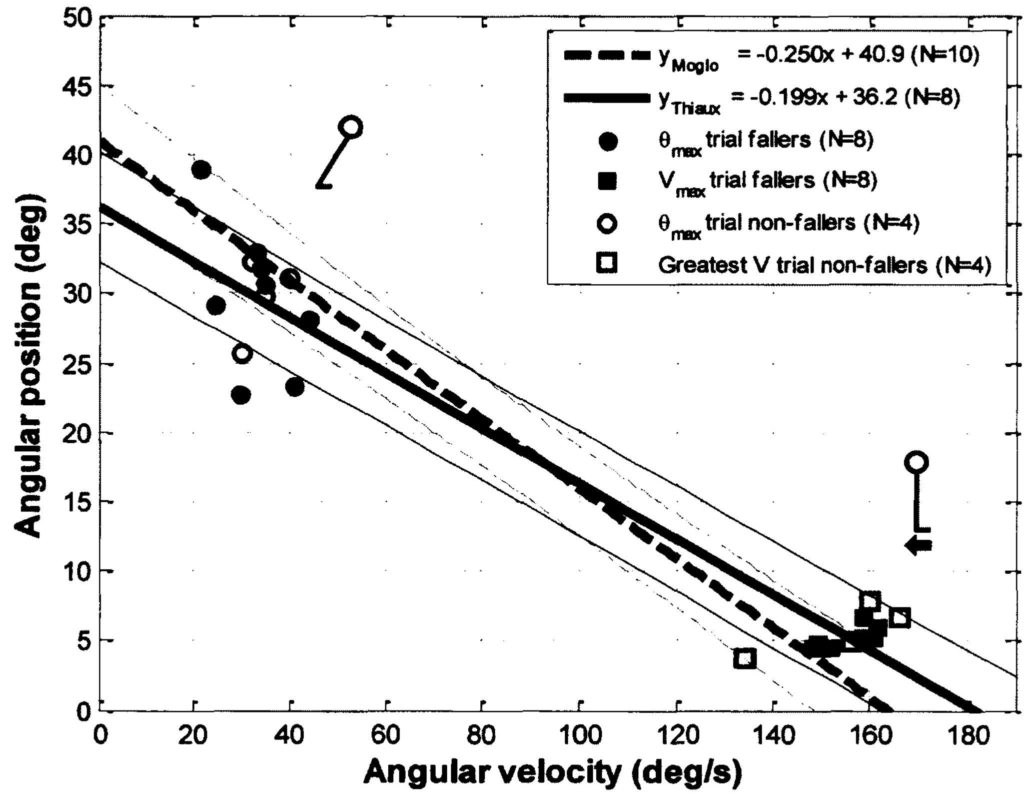

Figure 2.4 : The perturbation threshold line, i.e., the linear regression between the angular positions and velocities at the end of reaction time for lean release (filled circles) and surface translation (filled squares) trials at the threshold of balance recovery, for the 8 fallers (thick and thin full lines: mean ± standard deviation, r^2=0.928).
This perturbation threshold line was very similar to the one obtained by Moglo and Smeesters (2005) using lean releases, lean releases with waist pulls and waist pulls while walking with 10 younger adults (thick and thin dashed lines: r^2=0.827). Moreover, the angular position and velocity points at the end of reaction time for the maximum initial lean angle (empty circles) and the greatest surface translation velocity (empty squares) trials of 3 of the 4 non-fallers (75%) were within one standard deviation of this study's perturbation threshold line.

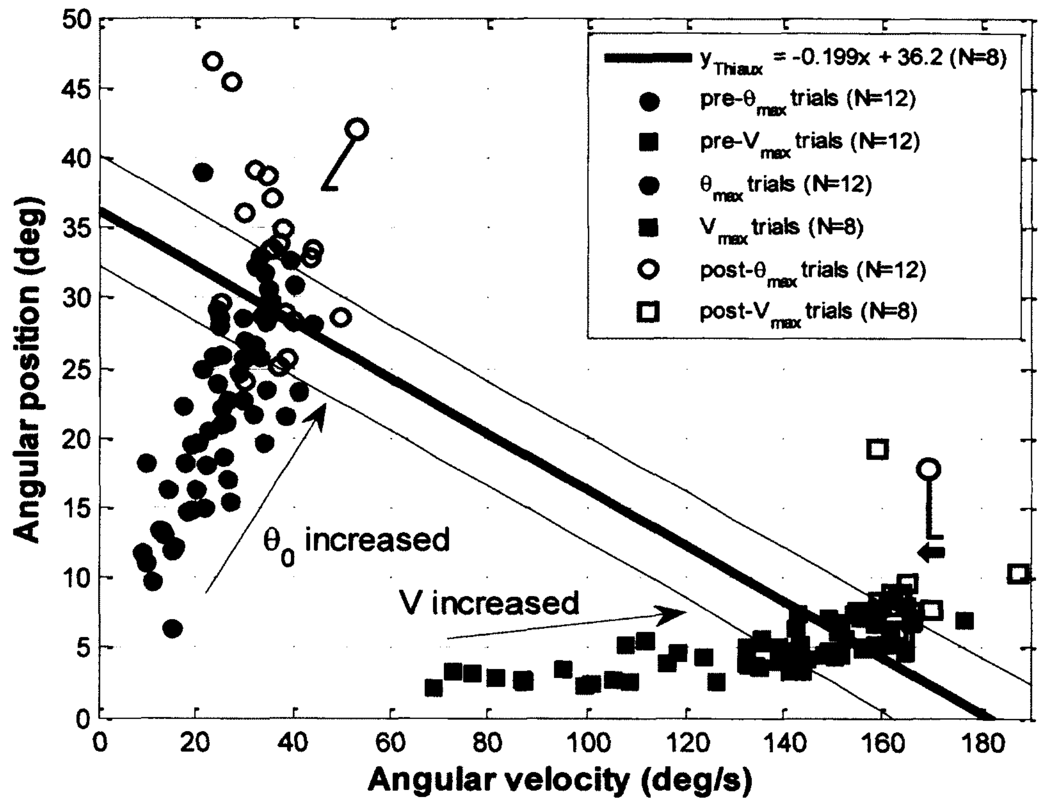

Figure 2.5: The perturbation threshold line from Figure 2.4, obtained from the successful maximum initial lean angle (filled black circles) and maximum surface translation velocity (filled black squares) trials of the 8 fallers, separates falls from recoveries (thick and thin full lines: mean ± standard deviation). Indeed, as the initial lean angle (θ_o) or surface translation velocity (V) increased, the angular position and velocity points at the end of reaction time got closer to the perturbation threshold line. Nevertheless, 96% of the angular position and velocity points at the end of reaction time for lean release (filled gray circles) and surface translation (filled gray squares) trials before the threshold of balance recovery, where balance recovery was successful, were below the mean plus one standard deviation. Furthermore, 97% of the angular position and velocity points at the end of reaction time for lean release (empty gray circles) and surface translation (empty gray squares) trials after the threshold of balance recovery, where participants failed to recover balance, were above the mean minus one standard deviation. Note that, although the 4 non-fallers never failed to recover balance for surface translations, they did reach a threshold of balance recovery for lean releases. The angular position and velocity points at the end of reaction time for these 4 successful maximum initial lean angle trials were thus also symbolized using filled black circles.

It is important to note that the longer weight transfer times, shorter step times, slower step velocities and shorter step lengths for maximum translation velocity trials compared to maximum lean angle trials could have been affected by our experimental setup. For safety reasons, both lean releases and surface translations were conducted on top of a firm gymnasium mat (8ft or

2.4m long). For lean releases, participants started ~0.3m from one end of the mat and had nearly 2.1m of mat to recover balance by stepping (Figure 2.2a). However, for surface translations, participants started in the middle of the mat, were translated backward 0.7m and then had 1.9m of mat to recover balance by stepping (Figure 2.2b). Some participants later reported being afraid of stepping off the mat during surface translations, given that the initial impression was of only 1.2m of mat available for stepping. Even though 1.2m was sufficient for even the longest step length, participants may have taken smaller step lengths in shorter step times, which lead to slower step velocities and perhaps smaller maximum translation velocities. This is fairly consistent with Telonio and Smeesters (2009), which showed using lean releases that as the amplitude of the perturbation decreased, weight transfer times were longer, step times were longer, step velocities were slower and step lengths were smaller. These results should thus be validated in future experiments.

Results suggest that the 4 participants who never failed to recover balance even at the greatest surface translation velocity were very close to their maximum translation velocities. A single additional surface translation velocity increment would have probably done the trick. Indeed, maximum lean angles for lean releases were not significantly different between surface translation fallers and non-fallers. Moreover, results of the effect of the two postural perturbations on response initiation, execution and geometry variables considering both fallers and non-fallers (N=12) were very similar to those obtained with only fallers (N=8, Table 2.1). Finally, the angular position and velocity points at the end of reaction time of 3 of the 4 non-fallers were within one standard deviation of the perturbation threshold line for both the maximum lean angle and the greatest translation velocity trials (Figure 2.4).

The dimensionless perturbation threshold line method to compare results from different postural perturbations has now been experimentally established for lean releases, lean releases with waist pulls, waist pulls while walking and surface translations, thus providing further evidence that the choice of postural perturbation does not affect the threshold of balance recovery. Therefore, as concluded by Mansfield and Maki (2009), when postural perturbation predictability and instruction given to the participant are similar, it does indeed appear that differences in the mechanical and sensory stimuli of each perturbation are much less important than differences in perturbation amplitude and timing. Finally, as the stability boundary method by Pai et al. (2000) established a threshold in center of mass position versus velocity phase space between feet in place and stepping balance recovery strategies, the perturbation threshold line method by Moglo and Smeesters (2005; 2006) established a threshold in participant angular position versus velocity phase space between balance recoveries and unavoidable falls, regardless of the postural perturbation. Being able to compare results across postural perturbations should therefore help researchers make faster and broader conclusions about balance recovery abilities and thus make these results more readily available to clinicians for fall prevention and rehabilitation. Indeed, results from any of the five postural perturbations should be applicable to the other four.

2.7 Acknowledgements

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Table 2.1: Effect of the two postural perturbations on the kinematic variables at the maximum lean angles or maximum translation velocities (mean ± standard deviation)

	Postural perturbation	Gender	Maximum Lean angle or Translation velocity	Reaction time (ms)	Weight transfer time (ms)	Step time (ms)	Step velocity (m/s)	Step length (mm)	Step angle (deg)	Modified lean angle (deg)	Angular ratio
			θ_{max} or V_{max}	RT	WTT	ST	SV	SL	α_c	β_c	$AR=\alpha_c/\beta_c$
N=8 (fallers only)	**Lean release**	**YW**	26.7±3.7deg	92±5	143±18	216±44	4.23±0.14	915±193	74.5±15.2	41.6±4.9	1.78±0.19
		YM	28.6±9.1deg	98±8	135±26	195±19	5.01±0.55	973±96	77.3±2.6	38.8±3.0	2.00±0.11
		Total	27.4±5.7deg	95±7	140±20	208±37	4.52±0.51	936±158	75.5±11.6	40.6±4.3	1.86±0.19
	Surface translation	**YW**	2.20±0.41m/s	98±6	156±31	164±21	4.11±0.27	676±97	52.2±7.9	40.0±4.3	1.31±0.15
		YM	2.33±0.14m/s	100±3	177±18	162±20	3.99±0.60	654±171	51.7±13.3	40.7±4.8	1.28±0.32
		Total	2.25±0.33m/s	99±5	164±28	164±19	4.07±0.38	668±118	52.0±9.3	40.2±4.2	1.30±0.21
	$p_{Perturbation}$			0.179	0.084	**0.004**	**0.038**	**<0.001**	**<0.001**	0.818	**<0.001**
	Perturbation difference	**Mean**				45	0.46	269	23.5		0.56
		95% CI				20/69	0.03/0.88	167/370	14.9/32.2		0.36/0.77
N=12 (fallers & non-fallers)	**Lean release**	**YW**	26.8±3.4deg	95±7	137±22	223±43	4.25±0.13	947±191	75.8±14.0	42.1±4.5	1.79±0.17
		YM	27.7±6.2deg	100±6	124±26	197±22	5.02±0.47	982±87	74.1±6.1	37.7±3.5	1.97±0.10
		Total	27.3±4.8deg	97±7	131±24	210±35	4.64±0.52	965±143	75.0±10.3	39.9±4.5	1.88±0.16
	Surface translation	**YW**	2.29±0.43m/s	101±8	152±30	168±21	4.15±0.26	699±103	54.6±9.1	39.9±3.9	1.37±0.20
		YM	2.54±0.25m/s	103±8	162±24	164±16	4.27±0.50	702±123	52.5±8.7	40.0±3.1	1.32±0.21
		Total	2.42±0.36m/s	102±8	157±27	166±18	4.21±0.39	700±108	53.5±8.6	40.0±3.3	1.34±0.20
	$p_{Perturbation}$			0.090	**0.010**	**<0.001**	**0.013**	**<0.001**	**<0.001**	0.948	**<0.001**
	Perturbation difference	**Mean**			-27	44	0.42	264	21.4		0.54
		95% CI			-45/-8	26/62	0.11/0.74	199/329	15.7/27.2		0.39/0.68

YM: Younger Men, YW: Younger Women. Significant p-values ($p \leq 0.05$) are **bolded**.

CHAPTER 3 THEORETICAL PUBLICATION

3.1 Preface

Authors and affiliation:

V. Thiaux: Masters' student, Université de Sherbrooke, Faculty of Engineering, Mechanical Engineering Department.

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Date of submission: February 1st 2014

Journal: Journal of Biomechanics

English title: Modeling the Lean Release and Surface Translation Perturbations with an Inverted Pendulum on a Skid

French title: Modélisation des perturbations de relâchement d'une inclinaison et de translation de surface avec un pendule inversé sur une plateforme glissante

Contribution to the document:

This article contributes to this master's thesis by answering the theoretical specific aim, which is to determine if a two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid could simulate the angular position and velocity of participants from onset of perturbation to onset of response for both lean releases and surface translations.

French abstract:

Les expériences sur le rétablissement de l'équilibre prennent du temps, sont couteuses et potentiellement dangereuses, et peuvent être très exigeantes et fatigantes pour les personnes âgées frêles. Il serait donc utile d'utiliser un modèle plutôt qu'une expérience

pour prédire théoriquement si une perturbation posturale donnée entrainera une chute inévitable ou si un rétablissement de l'équilibre sera possible pour un participant donné. Ceci semblait possible considérant que a) des modèles de pendules inversés ont été utilisés avec succès pour modéliser des relâchements d'inclinaison, tirages à la taille, translations de surface et trébuchements, et b) une série de quatre études expérimentales ont démontré que les relâchements d'inclinaison, tirages à la taille et translations de surface sont suffisamment similaires qu'elles peuvent être comparées. Nous avons donc utilisé un modèle en deux dimensions de pendule inversé à barre mince monté sur une palette glissante bougeant horizontalement pour simuler la position et la vitesse angulaire de jeunes adultes de l'initiation de la perturbation à l'initiation de la réponse pour les relâchements d'inclinaison et translations de surface d'une étude expérimentale récente. Les résultats ont démontré que la majorité des erreurs moyennes quadratiques et erreurs au temps de réaction entre les positions et vitesses angulaires expérimentales et théoriques étaient respectivement de moins de 2% et 4%. Seule l'erreur moyenne quadratique de vitesse angulaire pour les translations de surface était plus grande mais tout de même moins de 9%. Plus important encore, les positions et vitesses angulaires théoriques à la fin du temps de réaction pour les essais aux angles d'inclinaison et vitesses de translation maximum formaient une ligne de perturbation limite séparant les chutes des rétablissements qui était très similaire à celles obtenues précédemment dans deux études expérimentales.

Note: Following the corrections requested by the members of the jury, the content of this article differs from the one submitted.

Original article for Journal of Biomechanics
Submitted February 2014

Modeling the Lean Release and Surface Translation Perturbations with an Inverted Pendulum on a Skid

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3.2 Abstract

Balance recovery experiments are time consuming, expensive, can be dangerous and can be very demanding and fatiguing for frail older adults. It would thus be useful to use a model instead of an experiment to theoretically predict if a given postural perturbation will lead to an unavoidable fall or if balance recovery is possible for a given participant. This appeared to be possible given that: a) inverted pendulum models have been successfully used to model lean releases, waist pulls, surface translations and trips, and b) a series of four experimental studies have shown that lean releases, waist pulls and surface translations are similar enough that they can be compared. We thus used a two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid to simulate the angular position and velocity of younger adults from onset of perturbation to onset of response for lean releases and surface translations from a recent experimental study. Results showed that the majority of root mean square errors and errors at reaction time between the experimental and theoretical angular positions and velocities were less than 2% and 4%, respectively. Only the angular velocity root mean square error for surface translations was greater but still less than 9%. More importantly, the theoretical angular positions and velocities at the end of reaction time for maximum lean angle and maximum translation velocity trials formed a perturbation threshold line separating falls from recoveries that was very similar to the ones obtained previously in two experimental studies.

Abstract Word Count: 248 / 250 words

3.3 Introduction

Balance recovery experiments are time consuming, expensive and can be dangerous, especially if large postural perturbations at the threshold of balance recovery, were avoiding a fall is not always possible, are used. More importantly, balance recovery experiments can be very demanding and fatiguing for frail older adults. It would thus be useful to be able to use a model instead of an experiment to theoretically predict if a given postural perturbation will lead to an unavoidable fall or if balance recovery is possible for a given individual participant. Indeed, theoretical models are usually faster and much less expensive than experiments. They are also not dangerous and never complain or get tired no matter how many times you run them.

Five different postural perturbations have been modelled using medium to large postural perturbations: lean releases, waist pulls, surface translations, slips and trips. However, we must first mention the one-, two- and three-segment two-dimensional models developed by van den Kroonenberg *et al.* (1995) to simulate self-initiated falls, which to our knowledge were the first published models of falls from standing height. Six different studies have simulated lean releases using either two-dimensional inverted pendulum models (Aftab *et al.*, 2012; Hsiao and Robinovitch, 1999; Smeesters, 2009) or two- (Lo and Ashton-Miller, 2008a) and three-dimensional (Lo and Ashton-Miller, 2008b; Thelen and Burd, 2000) multi-segment models. While some simply fell under gravity (Smeesters, 2009), others used springs (Hsiao and Robinovitch, 1999), actuators (Lo and Ashton-Miller, 2008a; 2008b; Thelen and Burd, 2000) or controllers (Aftab *et al.*, 2012) to more accurately simulate balance recovery by stepping. To our knowledge, only one study simulated waist pulls using a two-dimensional inverted pendulum model simply falling under gravity (Smeesters, 2009). Only one study simulated surface translations using two two-dimensional inverted pendulum models and the work-energy principle to more accurately simulate single step balance recovery (Wu *et al.*, 2007). Only one study simulated slips using a three-dimensional multi-segment model simply falling under gravity (Smeesters *et al.*, 2007). Finally, five different studies have simulated forward trips using either two-dimensional inverted pendulum models (Forner Cordero *et al.*, 2004; Roos *et al.*, 2010; van den Bogert *et al.*, 2002) or three-dimensional multi-segment models (Shiratori *et al.*, 2009; Smeesters *et al.*, 2007). While some simply fell under gravity

(Smeesters *et al.*, 2007; van den Bogert *et al.*, 2002), others used springs (Roos *et al.*, 2010), actuators (Forner Cordero *et al.*, 2004) or controllers (Shiratori *et al.*, 2009) to more accurately simulate balance recovery by stepping.

Various forms of two-dimensional inverted pendulum models have thus been successfully used to model all but one postural perturbation: lean releases, waist pulls, surface translations and trips. Could a single inverted pendulum model be used to model all five postural perturbations? For this to be possible, postural perturbations would have to be similar enough to be comparable.

To our knowledge only four experimental studies have attempted to compare results from different postural perturbations. Mansfield and Maki (2009) compared medium waist pulls and surface translations while standing and walking in place in multiple directions and in both younger and older adults. They concluded that differences in the mechanical and sensory stimuli of each perturbation were less important than differences in perturbation amplitude and timing. However, amplitudes can be difficult to compare (waist pull force versus surface translation acceleration). Moglo and Smeesters (2005; 2006) compared large forward lean releases, lean releases with waist pulls and waist pulls while walking in both younger and older adults at the threshold of balance recovery, which helped resolve the difficulty in comparing postural perturbation amplitudes. Indeed, the threshold of balance recovery in these studies were the maximum initial lean angle and the maximum waist pull force that participants could be suddenly released from or could suddenly sustain and still recover balance using a single step for lean releases with or without waist pulls and waist pulls while walking, respectively. Their results showed that, the three postural perturbations gave different results (Figure 3.1, thick dashed lines and filled symbols). However, from onset of perturbation to onset of response, their results were similar enough that they could be compared. Indeed, the angular positions and velocities at the end of reaction time of the threshold trials formed a perturbation threshold line (Figure 3.1, thin solid and dashed lines and empty black symbols) separating falls (Figure 3.1, white area) from recoveries (Figure 3.1, gray area), regardless of the postural perturbation. Finally, the perturbation threshold line obtained by Thiaux *et al.* (2014, submitted) for lean releases and surface translations was very similar to the one obtained by Moglo and Smeesters (2005).

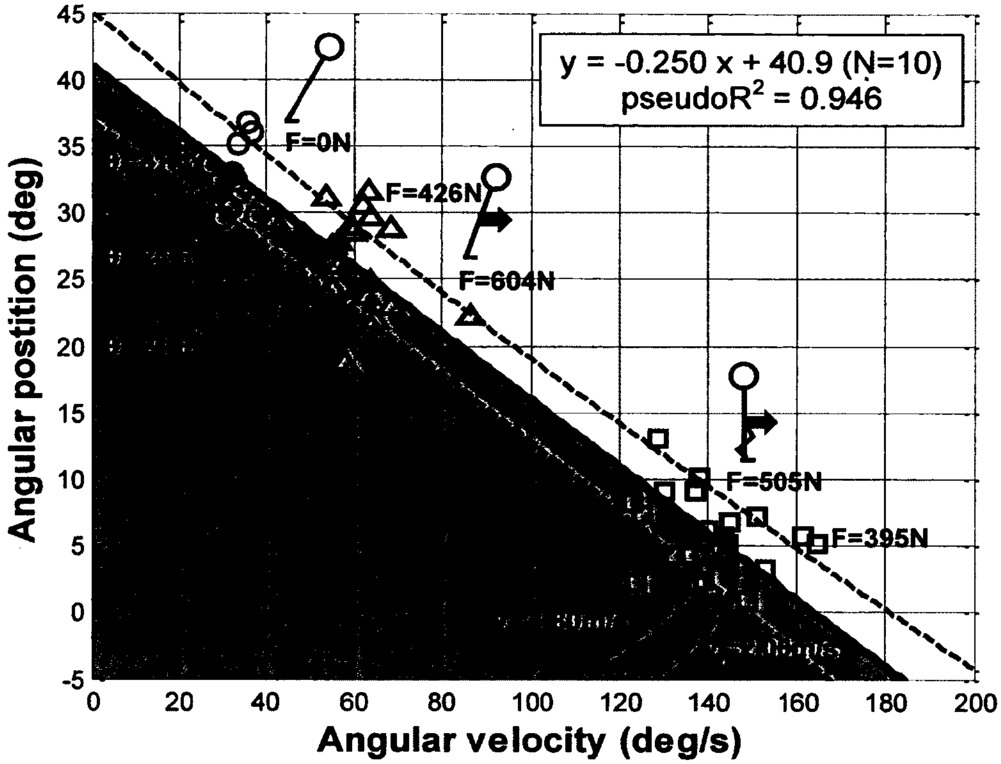

Figure 3.1: Perturbation threshold line for lean releases (circles), lean releases with waist pulls (triangles) and waist pulls while walking (squares) at the threshold of balance recovery separates falls from recoveries (adapted with permission from Moglo and Smeesters, 2005). Increasing waist pull force decreased the maximum lean angles and increasing walking velocity decreased the maximum waist pull forces (thick dashed lines ending in filled symbols). The angular positions and velocities (empty symbols) at the end of reaction time for the successful threshold trials at the maximum lean angle, maximum lean angle with waist pull and maximum waist pull while walking formed the perturbation threshold line (thin solid and dashed lines: mean ± standard deviation). Trials before the threshold of balance recovery where balance recovery was successful were in the gray area below the perturbation threshold line, while trials after the threshold of balance recovery where participants failed to recover balance were in the white area above the perturbation threshold line.

The purpose of this study was thus to determine if a two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid could simulate the angular position and velocity of participants from onset of perturbation to onset of response for both the lean releases and surface translations from Thiaux *et al.* (2014, submitted).

3.4 Methods

3.4.1 Experimental methods

Participants

Experimental data was obtained from a previous study which determined: 1) the maximum forward initial lean angle from which 12 healthy younger men and women (mean±SD=26.2±3.4yrs, range=22-32yrs; 1.60±0.11m; 66.0±17.1kg) could be suddenly released and still recover balance using a single step, and 2) the maximum backward surface translation velocity from which each participant could be suddenly pulled and still recover balance using a single step (Thiaux *et al.*, 2014, submitted).

Experimental procedure

Balance recoveries from both lean releases and surface translations were conducted on top of a firm gymnasium mat and using a safety harness attached to an overhead rail (Thiaux *et al.*, 2014, submitted). For lean releases, the initial lean angle started at 10deg, was increased in 5deg and ultimately 2.5deg increments after each successful trial, until participants failed to recover balance twice at a given initial lean angle. For surface translations, the surface translation velocity of a rubber sheet pulled by a linear motor (T4D, Trilogy System Corporation, Webster TX) started at 1m/s and was increased in 0.25m/s increments after each successful trial, until participants failed to recover balance twice at a given surface translation velocity (with constant displacement=700mm and acceleration=25m/s^2, Figure 3.2). The threshold of balance recovery was thus the last successful trial at the maximum initial lean angle or maximum surface translation velocity, respectively. Balance recovery was successful if participants used no more than one step, did not touch the mat with their hands, and did not support their body weight in the safety harness.

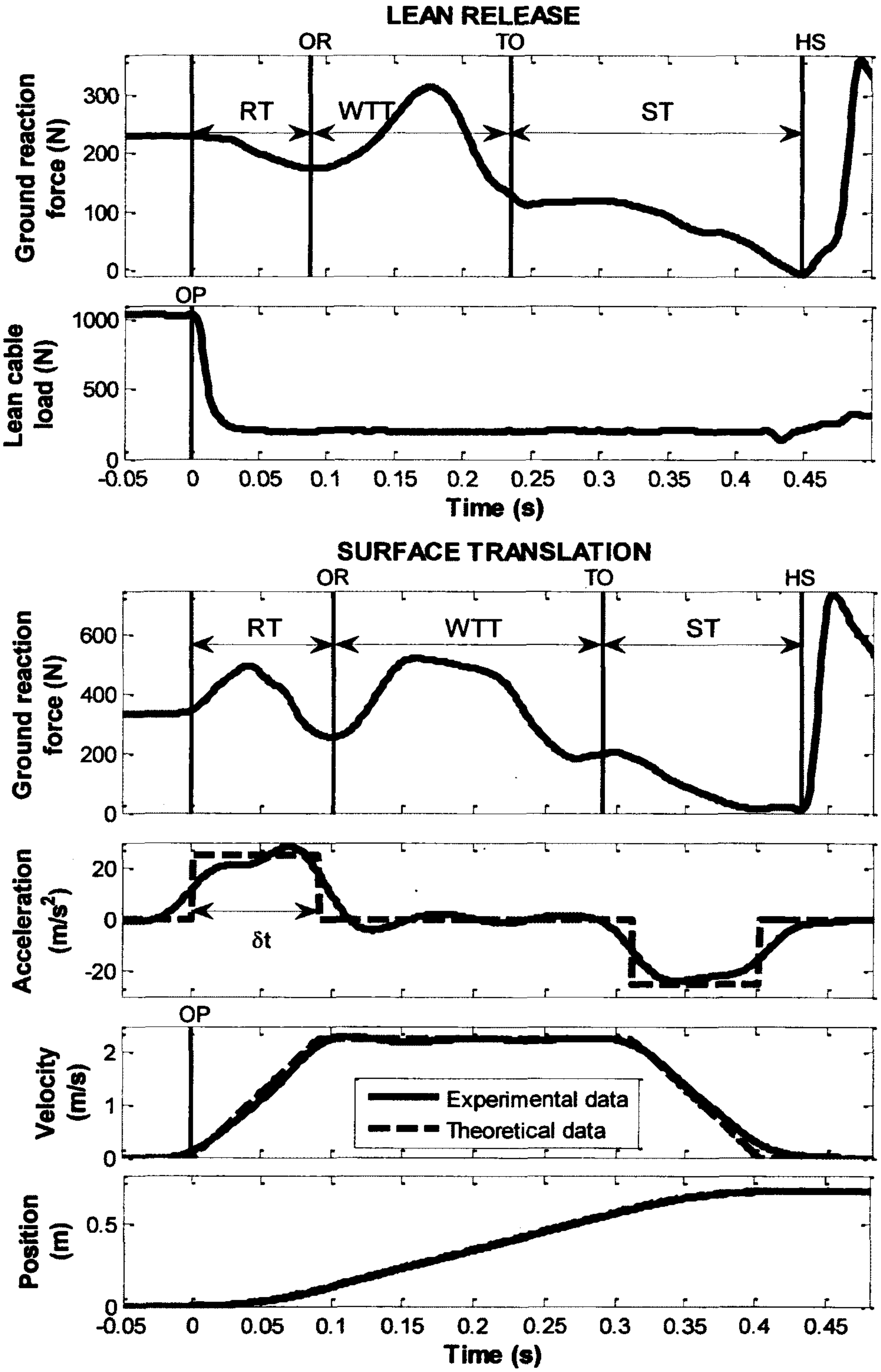

Figure 3.2: Time histories for lean releases (top two graphs) and surface translations (bottom four graphs) for a typical participant at the threshold of balance recovery, i.e., at the maximum initial lean angle and the maximum surface translation velocity, respectively.

For lean releases, vertical ground reaction force (top) and the force on the lean cable (bottom) are shown. For surface translations (from top to bottom), vertical ground reaction force and the surface translation acceleration, velocity and position are shown. Also shown are reaction time (RT) from onset of perturbation (OP) to onset of response (OR), weight transfer time (WTT) from OR to toe off (TO), and step time (ST) from TO to heel strike (HS), as detailed in Thiaux *et al.* (2014, submitted). For surface translations, note that the initial increase in ground reaction force at the onset of perturbation is an artefact caused by the rubber sheet pushing down on the gymnasium mat as it is suddenly pulled backward. Note also that the experimental surface translation, as measured by the marker on the linear motor, was a very good match to the theoretical surface translation programmed into the linear motor. In particular, the experimental width at half maximum of the positive acceleration step was a very good match to the theoretical width of the positive acceleration step programmed into the linear motor (δt_{error}=5±6ms).

Measuring instruments and variables

Kinematic and kinetic data were recorded at 100 and 1000Hz, respectively, using 8 optoelectronic sensors with 18 passive markers (Motion Analysis Inc., Santa Rosa CA), 2 force plates (FP 3060-15 and FP 6090-15, Bertec corporation, Colombus OH) and a single degree of freedom load cell (MLP-500, Transducer Techniques, Temecula CA). Both data were synchronised, filtered and processed using Matlab (Mathworks, Natick MA), as detailed in Thiaux *et al.* (2014, submitted).

For both postural perturbations, the main variables were the angular position (θ) and velocity (ω, (Thiaux *et al.*, 2014, submitted)). The angular position was measured as the sagittal plane angle between the vertical and the line connecting the midpoints of the medial and lateral malleoli of the stance foot and the two greater trochanters. For surface translations, the anterior-posterior position (x), velocity ($\dot{x}$) and acceleration ($\ddot{x}$) of the marker on the linear motor were also measured (Figure 3.2).

These variables were measured during the reaction time (RT, (Thiaux *et al.*, 2014, submitted)), the time difference between onset of response (OR) and onset of perturbation (OP, Figure 3.2). Onset of perturbation occurred when the lean cable load started decreasing or the surface translation velocity started increasing. Onset of response occurred when the vertical ground reaction force started increasing (at inflection point), ignoring the artefact at the onset of surface translation.

3.4.2 Theoretical methods

Inverted pendulum on a skid model

The lean release and surface translation postural perturbations were simulated in Matlab using a thin rod inverted pendulum mounted on a horizontally moving skid model in the sagittal plane (Figure 3.3, Appendix A - Inverted pendulum on a skid model equations). The inputs were the masses of the participant (m) and skid (M), height of the participant (h), gravity (g=9.81m/s^2), waist pull force ($\overrightarrow{F_1}$), rubber sheet pull force ($\overrightarrow{F_2}$), coefficient of friction between the rubber sheet and the mat (μ) and ankle torque ($\vec{\tau}$). The outputs were the angular and translational positions (θ and x), velocities (ω and $\dot{x}$) and accelerations (α and $\ddot{x}$) from onset of perturbation at t=0 to onset of response at reaction time.

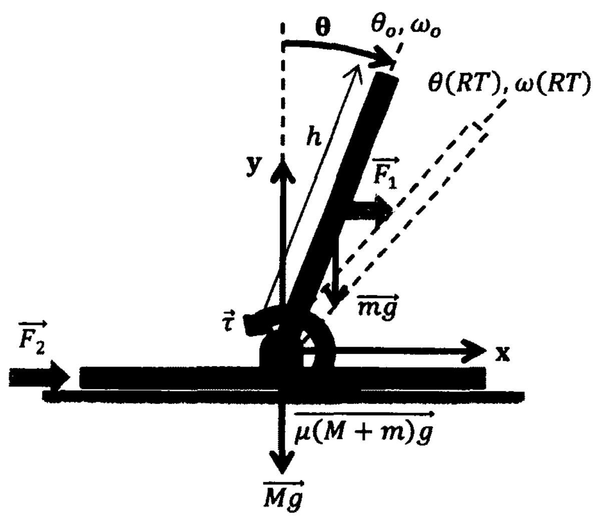

Figure 3.3: Inverted pendulum on a skid model to simulate lean releases and surface translations.
Inputs: participant mass (m), skid mass (M), participant height (h), gravity (g), waist pull force ($\overrightarrow{F_1}$), rubber sheet pull force ($\overrightarrow{F_2}$), coefficient of friction between the rubber sheet and mat (μ) and ankle torque ($\vec{\tau}$). Outputs: angular and translational positions (θ and x), velocities (ω and $\dot{x}$) and accelerations (α and $\ddot{x}$), from onset of perturbation at t=0 to onset of response at reaction time (RT).

Theoretical procedure

The mass (m) and height (h) of the model were adjusted according to each participant simulated. For lean releases, the inputs were $M=\infty$, $\vec{F_1}=0$, $\vec{F_2}=0$, $\mu=0$ and $\vec{\tau}=0$,[1] and the initial conditions were the initial lean angle (θ_o) and angular velocity ($\omega_o\approx 0$) for the trial simulated, $x_o=0$ and $\dot{x}_o=0$. For surface translations, the inputs were:

- M=30kg: The sum of the masses of the rubber sheet, the moving carriage assembly of the linear motor and all the attachment hardware.
- $\vec{F_1}=0$
- $\vec{F_2}=(M+m)\ddot{x}$, where $\ddot{x}$ was modelled as a step2 (Figure 3.2): Its amplitude was equal to the maximum positive acceleration for the trial simulated ($\ddot{x}$=25.9±1.7m/s2), but never exceeded the theoretical amplitude programmed into the linear motor of 25.0m/s2. Its width was equal to the width at half maximum of the positive acceleration step for the trial simulated (δt=44-120ms).
- μ=0.0078551m+0.16405: The optimal μ was determined for the 12 trials at the maximum surface translation velocity using the inverted pendulum on a skid model by minimizing the error between the experimental and theoretical angular position (δθ) and velocity (δω) at reaction time (Figure 3.4). A linear regression was then established between m and the optimal μ (Figure 3.5). As the experimental setup was no longer available, this was the best available estimate of μ.
- $\vec{\tau}=0$

and the initial conditions were $\theta_o=0$, $\omega_o=0$, $x_o=0$ and $\dot{x}_o=0$.

[1] This is validated by the fact that δx_{RMS}=0±0mm and δx_{RT}=0±0mm, for lean releases.
[2] This is validated by the fact that δx_{RMS}=13±4mm/700mm=2±1% and δx_{RT}=6±9mm/700mm=1±1%, for surface translations.

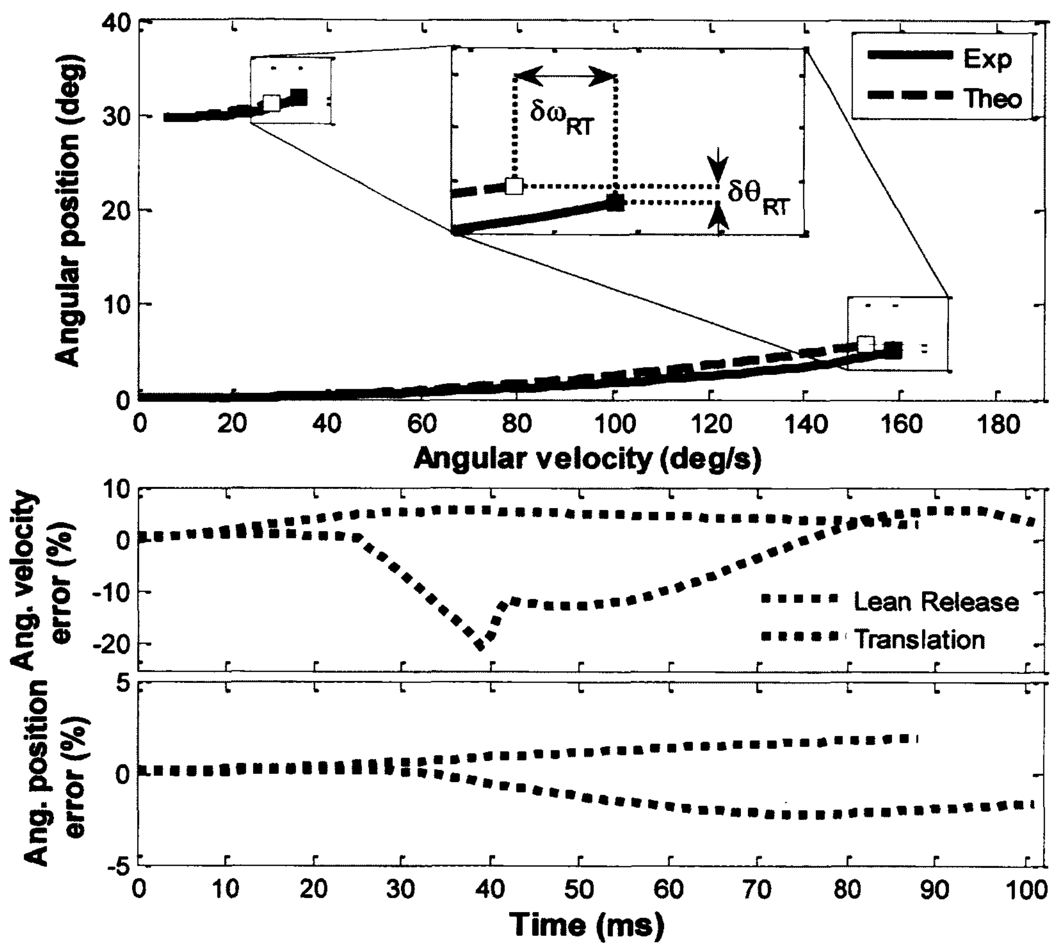

Figure 3.4: Angular position as a function of angular velocity from onset of perturbation at t=0 to onset of response at reaction time (top graph), for 2 typical trials at the maximum initial lean angle (gray) and maximum surface translation velocity (black).
Both the experimental data (full lines) and the theoretical data using the inverted pendulum on a skid model (dashed lines) are shown. The errors between the experimental (filled squares) and theoretical (empty squares) angular position ($\delta\theta_{RT}$) and velocity ($\delta\omega_{RT}$) at reaction time are also shown (inset top graph). Finally, the normalized errors (dotted lines) between the experimental and theoretical angular position ($\delta\theta/y_{intercept}$, bottom graph) and velocity ($\delta\omega/x_{intercept}$, middle graph) from onset of perturbation at t=0 to onset of response at reaction time are shown for these typical lean release (gray lines) and surface translation (black lines) trials at the threshold of balance recovery. The x and y intercepts are from the experimental perturbation threshold line (Figure 3.6).

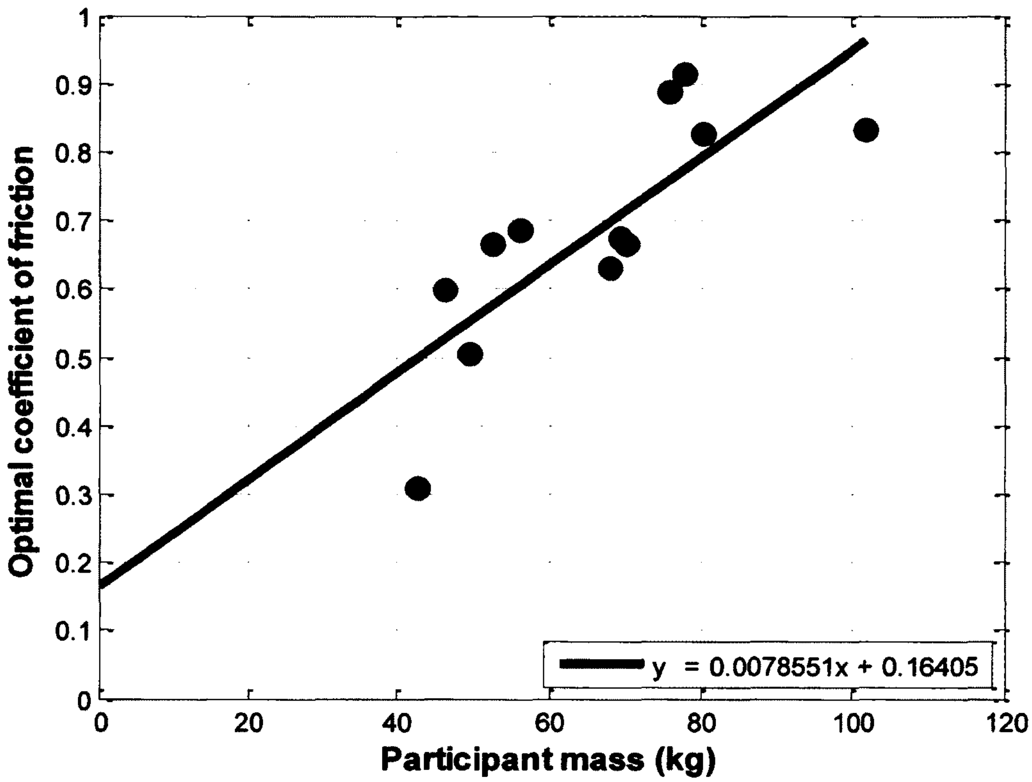

Figure 3.5: Linear regression (r^2=0.622) between the participant mass (m) and the optimal coefficient of friction between the rubber sheet and the mat (μ) for the maximum surface translation velocity trials using the inverted pendulum on a skid model.

3.4.3 Data analysis

Data were analysed using SPSS (SPSS Inc., Chicago IL) and $p \leq 0.05$ were significant. First, the error between the experimental and theoretical angular positions ($\delta\theta$) and velocities ($\delta\omega$) was calculated from onset of perturbation at t=0 (i=1) to onset of response at reaction time ($i=N_{RT}$), for trials both before and at the maximum lean angles or maximum translation velocities (Figure 3.4).

$$\begin{matrix} \delta\theta_i = \theta_{i\,exp} - \theta_{i\,theo} \\ \delta\omega_i = \omega_{i\,exp} - \omega_{i\,theo} \end{matrix} \quad \text{for } i = 1 \text{ to } N_{RT}$$

Single sample t-tests then determined if both the root mean square error from onset of perturbation to onset of response ($\delta\theta_{RMS}$ and $\delta\omega_{RMS}$) and the error at reaction time ($\delta\theta_{RT}$ and $\delta\omega_{RT}$) were significantly different from zero.

$$\delta\theta_{RMS} = \sqrt{\frac{\sum_{i=1}^{N_{RT}} \delta\theta_i^2}{N_{RT}}} \quad \text{and} \quad \delta\theta_{RT} = \delta\theta_{N_{RT}\,exp} - \delta\theta_{N_{RT}\,theo}$$

$$\delta\omega_{RMS} = \sqrt{\frac{\sum_{i=1}^{N_{RT}} \delta\omega_i^2}{N_{RT}}} \qquad \delta\omega_{RT} = \delta\omega_{N_{RT}\,exp} - \delta\omega_{N_{RT}\,theo}$$

Paired t-tests also determined the effect of the two postural perturbations on both the RMS error and the error at reaction time. Finally, for both the experimental and theoretical data, linear regressions were used to establish the relationships between the angular positions and velocities at the end of reaction time for trials at the threshold of balance recovery.

3.5 Results

For surface translations, 4 participants never failed to recover balance even at the greatest surface translation velocity (2.75m/s) achievable with the linear motor (Thiaux *et al.*, 2014, submitted). Therefore, significant differences from zero, postural perturbation effects and linear regressions for trials at the maximum lean angles or maximum translation velocities were evaluated with only the fallers (N=8).

3.5.1 Pre-maximum trials for fallers and non-fallers (N=12)

Considering both fallers and non-fallers for trials before the maximum lean angles or maximum translation velocities (Table 3.1), all RMS errors and errors at reaction time were significantly different from zero ($p<0.001$), except for $\delta\omega_{RT}$ for surface translations ($p=0.630$). Nevertheless, angular position and velocity errors were all smaller than 0.6deg (2%) and 7deg/s (4%), respectively, except for $\delta\omega_{RMS}$=16deg/s (9%) for surface translations. RMS errors for both angular positions (-95%CI/mean/+95%CI: 0.1/0.2/0.3deg, $p<0.001$) and velocities (7/9/11deg/s, $p<0.001$) were smaller for lean releases. However, errors at reaction time for both angular positions (1.0/1.2/1.4deg, $p<0.001$) and velocities (0/4/8deg/s, $p=0.035$) were greater for lean releases.

3.5.2 Maximum trials for fallers only (N=8)

Considering only fallers for trials at the maximum lean angles or maximum translation velocities (Table 3.1), all RMS errors and $\delta\theta_{RT}$ for lean releases were significantly different from zero ($p \leq 0.026$), but $\delta\theta_{RT}$ for surface translations (p=0.162) and $\delta\omega_{RT}$ for lean releases (p=0.257) and surface translations (p=0.079) were not. Nevertheless, angular position and velocity errors were all smaller than 0.7deg (2%) and 8deg/s (4%), respectively, except for $\delta\omega_{RMS}$=15deg/s (8%) for surface translations. While there was a trend for $\delta\omega_{RMS}$ to be smaller for lean releases (0/7/14deg/s, p=0.057), $\delta\theta_{RT}$ were greater for lean releases (0.3/1.1/1.8deg, p=0.011). However $\delta\theta_{RMS}$ (p=0.873) and $\delta\omega_{RT}$ (p=0.630) were not significant for postural perturbation effects.

3.5.3 Perturbation threshold line

Considering only fallers, the experimental linear regression between the angular positions and velocities at the end of reaction time for trials at the threshold of balance recovery (Thiaux *et al.*, 2014, submitted) was very similar to the theoretical one obtained using the inverted pendulum on a skid model (Figure 3.6). Moreover, both linear regressions were similar to the one obtained by Moglo and Smeesters (2005). Finally, the experimental angular position and velocity points at the end of reaction time for the maximum lean angle and the greatest translation velocity trials of 3 of the 4 non-fallers (75%) were within one standard deviation of the experimental linear regression (Thiaux *et al.*, 2014, submitted). Furthermore, the theoretical angular position and velocity points at the end of reaction time for the maximum lean angle trials of 4 of the 4 non-fallers (100%) and for the greatest translation velocity trials of 3 of the 4 non-fallers (75%) were within one standard deviation of the theoretical linear regression.

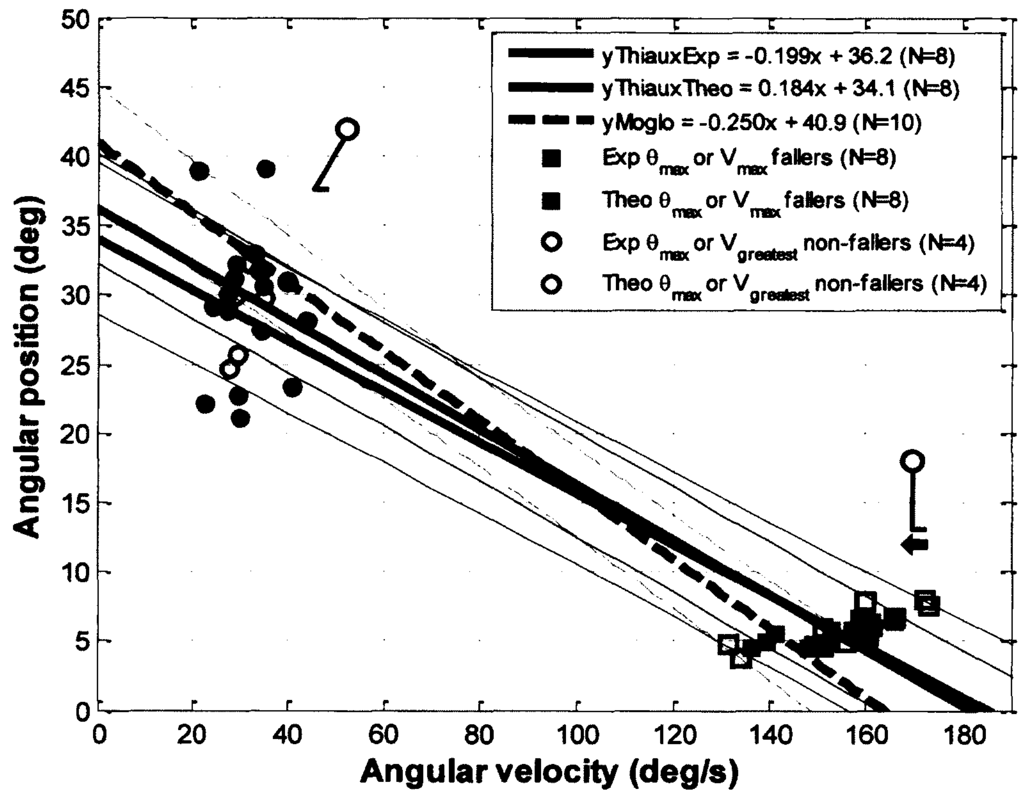

Figure 3.6: The experimental perturbation threshold line (thick and thin full black lines and filled black symbols: mean ± standard deviation, r^2=0.928, (Thiaux *et al.*, 2014, submitted)), i.e., the linear regression between the angular positions and velocities at the end of reaction time for lean release (circles) and surface translation (squares) trials at the threshold of balance recovery, for the 8 fallers (filled symbols).

This perturbation threshold line was very similar to the theoretical one obtained using the inverted pendulum on a skid model for the 8 fallers (thick and thin full gray lines and filled gray symbols: r^2=0.854), and to the one obtained by Moglo and Smeesters (2005) using lean releases, lean releases with waist pulls and waist pulls while walking with 10 younger adults (thick and thin dashed black lines: r^2=0.827). Finally, the experimental angular position and velocity points at the end of reaction time for the maximum initial lean angle (empty black circles) and the greatest surface translation velocity (empty black squares) trials of 3 of the 4 (75%) non-fallers (empty symbols) were within one standard deviation of the experimental perturbation threshold line (Thiaux *et al.*, 2014, submitted). Furthermore, the theoretical angular position and velocity points at the end of reaction time for the maximum initial lean angle trials (empty gray circles) of 4 of the 4 (100%) non-fallers and for the greatest surface translation velocity trials (empty gray squares) of 3 of the 4 (75%) non-fallers were within one standard deviation of the theoretical perturbation threshold line.

3.6 Discussion

The two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid did accurately simulate the angular position and velocity of participants from onset of perturbation to onset of response for both lean releases and surface translations. Indeed, results showed that the majority of root mean square errors and errors at reaction time between the experimental and theoretical angular positions and velocities were less than 2% and 4%, respectively (Table 3.1). Only the angular velocity root mean square error for surface translations was greater but still less than 9%. More importantly, the theoretical angular positions and velocities at the end of reaction time for maximum lean angle and maximum translation velocity trials formed a perturbation threshold line separating falls from recoveries (Figure 3.6) that was very similar to the ones obtained previously in experiments by Thiaux *et al.* (2014, submitted) and Moglo and Smeesters (2005).

These modeling results also provide additional evidence that the 4 participants who never failed to recover balance even at the greatest surface translation velocity were very close to their maximum translation velocities. Indeed, the experimental results (Thiaux *et al.*, 2014, submitted) showed that: a) the maximum lean angles for lean releases were not significantly different between surface translation fallers and non-fallers; b) the effect of the two postural perturbations on response initiation, execution and geometry variables considering both fallers and non-fallers (N=12) were very similar to those obtained with only fallers (N=8); and c) the angular position and velocity points at the end of reaction time of 3 of the 4 non-fallers were within one standard deviation of the experimental perturbation threshold line for both the maximum lean angle and the greatest translation velocity trials (Figure 3.6). Moreover, the theoretical results showed that the angular position and velocity points at the end of reaction time of 4 of the 4 non-fallers for the maximum lean angle trials and of 3 of the 4 non-fallers for the greatest translation velocity trials were within one standard deviation of the theoretical perturbation threshold line.

We had hoped that the addition of surface translations might fill in the gap in data points between 80-120deg/s and 10-20deg in the perturbation threshold line (Figure 3.1) previously obtained by Moglo and Smeesters (2005). This gap could not be filled without increasing waist pull forces beyond safe levels for both lean releases with waist pulls and waist pulls while walking, and unfortunately was not filled by the addition of surface translations. However, simulations with the inverted pendulum on a skid model suggest that it should be possible to fill the gap by using lean releases with surface translations or surface translations while walking.

The greatest limitation of the inverted pendulum on a skid model was the larger 9% angular velocity root mean square error for surface translations (Table 3.1 and Figure 3.4 bottom and middle graphs). The source of this error is two-fold: 1) the numerical error in first order centered finite differences on two points used to obtain angular velocities from angular positions acquired experimentally at 100Hz; and 2) the fact that rubber sheet pull force ($\overrightarrow{F_2}$) was modelled as a step rather than using the actual experimental impulse (Figure 3.2). Despite this limitation, errors at reaction time between the experimental and theoretical angular positions and velocities for surface translations were less than 2% and 3%, respectively.

The greatest strength of the inverted pendulum on a skid model was that it accurately simulated both lean releases and surface translations, as done previously by Aftab *et al.* (2012), Hsiao and Robinovitch (1999) and Smeesters (2009) for lean releases and Wu *et al.* (2007) for surface translations. It is even ready to simulate waist pulls, given the presence of the waist pull force ($\overrightarrow{F_1}$), as done previously by Smeesters (2009). It should even be possible to use it for trips and slips by setting $\overrightarrow{F_2}$ equal to the resulting impulsive ground contact force (van den Bogert *et al.*, 2002), as done previously by Forner Cordero *et al.* (2004), Roos *et al.* (2010), van den Bogert *et al.* (2002) for trips.

The simple inverted pendulum on a skid model could thus potentially be used to theoretically predict if any postural perturbation applied on an individual participant will lead to an unavoidable fall or if balance recovery is possible, reducing the need for time consuming, expensive and dangerous experiments. For example, we have used it to simulate future experiments to determine the best range and levels of lean releases with surface translations and surface translations while walking amplitudes to insure a good distribution of results as well as determine the specifications of the necessary equipment. Indeed, as the stability boundary method by Pai *et al.* (2000) established a threshold in center of mass position versus velocity phase space between feet in place and stepping balance recovery strategies, the perturbation threshold line method by Moglo and Smeesters (2005; 2006) established a threshold in participant angular position versus velocity phase space between balance recoveries and unavoidable falls, regardless of the postural perturbation. Being able to compare results across postural perturbations and simulate them using the inverted pendulum on a skid model should therefore help researchers make faster and broader conclusions about balance recovery abilities and thus make these results more readily available to clinicians for fall prevention and rehabilitation. Indeed, results from any of the five postural perturbations should be applicable to the other four. Furthermore, it may help design equipment that detects (maximum angular position and velocity combinations) or even prevents falls (maximum bus acceleration limit). Finally, it could one day help to identify individuals at risk for falls.

3.7 Acknowledgements

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Table 3.1: Errors (mean±SD) between the experimental and theoretical results for angular position ($\delta\theta$) and velocity ($\delta\omega$)

			RMS error from OP to OR					**Error at RT**				
			Lean Release		**Surface Translation**		**$p_{perturbation}$**	**Lean Release**		**Surface Translation**		**$p_{perturbation}$**
			Mean±SD	**$p_{\mu\neq0}$**	**Mean±SD**	**$p_{\mu\neq0}$**		**Mean±SD**	**$p_{\mu\neq0}$**	**Mean±SD**	**$p_{\mu\neq0}$**	
Pre-max	**N=12** fallers & non-fallers	$\delta\theta$ (deg)	0.3±0.2	***	0.6±0.2	***	**<0.001**	0.6±0.4	***	-0.6±0.7	***	**<0.001**
		$\delta\theta/y_{intercept}$	1±1%		2±1%			2±1%		-2±2%		
		$\delta\omega$ (deg/s)	7±4	***	16±5	***	**<0.001**	5±4	***	1±13		**0.035**
		$\delta\omega/x_{intercept}$	4±2%		9±3%			3±2%		0±7%		
Max	**N=8** fallers only	$\delta\theta$ (deg)	0.5±0.4	*	0.5±0.3	**	0.873	0.7±0.7	*	-0.4±0.7		**0.011**
		$\delta\theta/y_{intercept}$	1±1%		1±1%			2±2%		-1±2%		
		$\delta\omega$ (deg/s)	8±7	*	15±3	***	0.057	4±8		5±8		0.630
		$\delta\omega/x_{intercept}$	4±4%		8±2%			2±5%		3±4%		

OP: Onset of Perturbation, OR: Onset of Response, RT: Reaction Time.
The x and y intercepts are from the experimental perturbation threshold line (Figure 3.6).
Significantly different form zero: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Significant perturbation effects are **bolded**.

CHAPTER 4 DISCUSSION

This chapter presents various experimental and theoretical discussion items that could not be included in the previous two experimental and theoretical chapters due to words count limitations for the publications but that were still relevant in the context of this master's thesis.

4.1 Experimental discussion

4.1.1 Participant recruitment and instructions

Twenty healthy adults participated in this study (8 preliminary and 12 final participants) and all participants were students or employees at Simon Fraser University. They were recruited through electronic advertisements and word of mouth. All participants provided informed written consent and the experimental protocol was approved by the research and ethics committees of both Simon Fraser University and Université de Sherbrooke.

Participants were instructed to recover their balance with a single step. The following text was read before each perturbation: *"You have to recover your balance with a single step. You can move your toes or your heel after recovering your balance to stabilize yourself, but you must not move your toes and your heel. Otherwise, it will be considered a second step. If the cable on the overhead trolley becomes taught, it will also be a failure."*

4.1.2 Synchronisation delays for surface translations

During the preliminary (summer term 2011) and final (winter term 2012) data collections at Simon Fraser University, synchronisation problems were experienced: the force plate data was delayed compared to the marker data for surface translations, sometimes by nearly 200ms (Figure 4.1). Due to a lack of time during the data collection terms at Simon Fraser University, the analyses were done at the Université de Sherbrooke the following terms. The synchronisation problems were first detected in the preliminary data collections during the fall term of 2011. After modifying the experimental protocol and upon visual inspection of the final data collections during the winter term of 2012, it appeared to have been solved.

Unfortunately, upon more careful analysis during the summer term of 2012, some delays were still present in the final data collections. This section thus explains how it was identified and resolved during post processing.

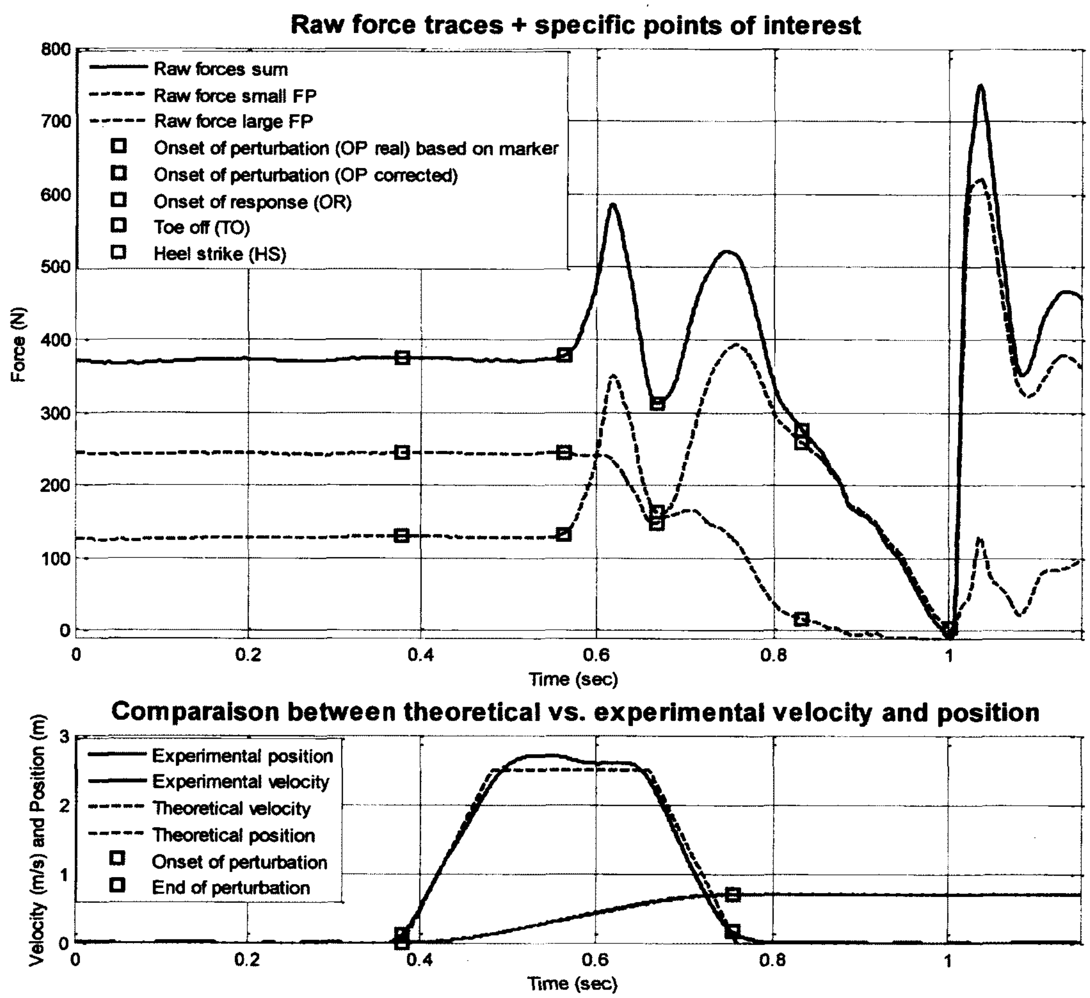

Figure 4.1: Synchronisation delay between the onset of perturbation obtained using the force plate ($OP_{FP\text{-}3SD}$, top graph) and marker (OP_{marker}, bottom graph) data for surface translations.

Hypotheses as to the source of the delays

Four main hypotheses as to the source of the delays were investigated:

1. The first hypothesis was a misuse of the Evart5.0 software, the data acquisition software used at Simon Fraser University. However, as the final data collections were done under supervision by one of the technicians from the Injury Prevention and Mobility Laboratory, this hypothesis was discarded.

2. The second hypothesis was a lack of power from the computer due to the large quantity of data acquired (Table 4.1). To reduce this potential source of synchronisation delays, the quantity of data acquired and the acquisition frequencies were reduced to a minimum for the final data collections. Although this helped to reduce the synchronisation delays, it did not completely resolve the issue.

Table 4.1: Reduction in the quantity of data acquired from experimental setup 1 to 3, for the preliminary data collections, to experimental setup 4 for the final data collections.

Setup	Equipment	Data	Frequency (Hz)	Location
1	EMG	2 x signals	1000	Left and right gastrocnemius
	Large force plate	F_x, F_y, F_z, M_x, M_y, M_z	1000	Beneath participant's feet
	Small force plate	f_x, f_y, f_z, m_x, m_y, m_z	1000	Beneath participant's feet
	Markers	26 x X, Y, Z	250	Temple (L&R), Acromion (L&R), Elbow (L&R), Wrist (L&R), Greater Trochanter (L&R), Thigh (L&R), Femoral epycondyles (L&R), Shinbone (L&R), Malleolus (Medial&Lateral, L&R), Metatarsal (Medial&Lateral , L&R), Linear motor, Rubber sheet
2	EMG	2 x signals	2000	Left and right gastrocnemius
	Large force plate	F_x, F_y, F_z, M_x, M_y, M_z	2000	Beneath participant's feet
	Small force plate	f_x, f_y, f_z, m_x, m_y, m_z	2000	Beneath participant's feet
	Markers	26 x X, Y, Z	125	Temple (L&R), Acromion (L&R), Elbow (L&R), Wrist (L&R), Greater Trochanter (L&R), Thigh (L&R), Femoral epycondyles (L&R), Shinbone (L&R), Malleolus (Medial&Lateral, L&R), Metatarsal (Medial&Lateral , L&R), Linear motor, Rubber sheet
3	EMG	2 x signals	1000	Left and right gastrocnemius
	1D load cell	F_{1DLC}	1000	Lean release pelvic belt
	Large force plate	F_z	1000	Beneath participant's feet
	Small force plate	f_z	1000	Beneath participant's feet
	Markers	22 x X, Y, Z	100	Temple (L&R), Acromion (L&R), Elbow (L&R), Wrist (L&R), Greater Trochanter (L&R), Femoral epycondyles (L&R), Malleolus (Medial&Lateral, L&R), Metatarsal (Medial&Lateral , L&R), Linear motor, Rubber sheet
4	1D load cell	F_{1DLC}	1000	Lean release pelvic belt
	Large force plate	F_z	1000	Beneath participant's feet
	Small force plate	f_z	1000	Beneath participant's feet
	Markers	18 x X, Y, Z	100	Temple (L&R), Acromion (L&R), Greater Trochanter (L&R), Femoral epycondyles (L&R), Malleolus (Medial&Lateral, L&R), Metatarsal (Medial&Lateral , L&R), Linear motor, Rubber sheet

EMG = Electromyography, L&R = Left and Right

3. The third hypothesis was that a Matlab coding error was made during data analysis. However, as the Matlab codes were checked line by line by Professor Smeesters during the summer term of 2012 and no errors were found, this hypothesis was discarded.
4. The fourth and last hypothesis was a hardware problem with the experimental setup for surface translations. For reasons that will be explained at the very end of this section and in the following section (4.1.3 - Synchronization impact tests), this appears to be the most likely source of the synchronisation problems.

Therefore, the 2 remaining hypotheses are a lack of power from the computer and a hardware problem. Unfortunately, it was impossible to investigate this further from the Université de Sherbrooke without regular access to the experimental setup. However, it should be looked into by the personnel at the Injury Prevention and Mobility Laboratory to avoid synchronisation problems with future studies. For the current study, even though it was clearly not optimal, the data was manually synchronised in post processing. To do so, four critical time points were identified using both force plate and marker data (Figure 4.1): onset of perturbation (OP), onset of response (OR), toe off (TO) and heel strike (HS).

Identifying onset of perturbation (OP)

Two different methods were used to identify the onset of perturbation using force plate data, the three standard deviation method ($OP_{FP\text{-}3SD}$) and the slope interpolation method ($OP_{FP\text{-}CTIF5}$). In the experimental setup, the rubber sheet on which the participant stood was slightly higher than the moving carriage assembly on the linear motor due to the thickness of the gymnasium mat (Figure 2.2). There was thus an initial increase in the sum of the vertical ground reaction forces at the onset of perturbation (Figure 4.1, top graph) caused by the rubber sheet pushing down on the gymnasium mat as it was suddenly pulled backward. This artifact was identified by the $OP_{FP\text{-}3SD}$ method (Figure 4.1, top graph) as the first time point when the sum of the vertical ground reaction forces exceeds three standard deviations of its mean value from zero to the onset of perturbation using marker data (OP_{Marker}). By the $OP_{FP\text{-}CTIF5}$ method (Figure 4.2), this artifact was identified as the time point at the intersection of two lines traced on the sum of the vertical ground reaction forces from 200ms prior to OP_{Marker} to 25ms after the peak of the artefact (100% of the amplitude):

- the horizontal line through the mean value of the sum of the vertical ground reaction forces during the stable phase (0% of the amplitude) between t_0 and t_1, representing 50% of the time interval;
- the line interpolating the vertical ground reaction forces from 15% to 35% of the total amplitude within the time interval.

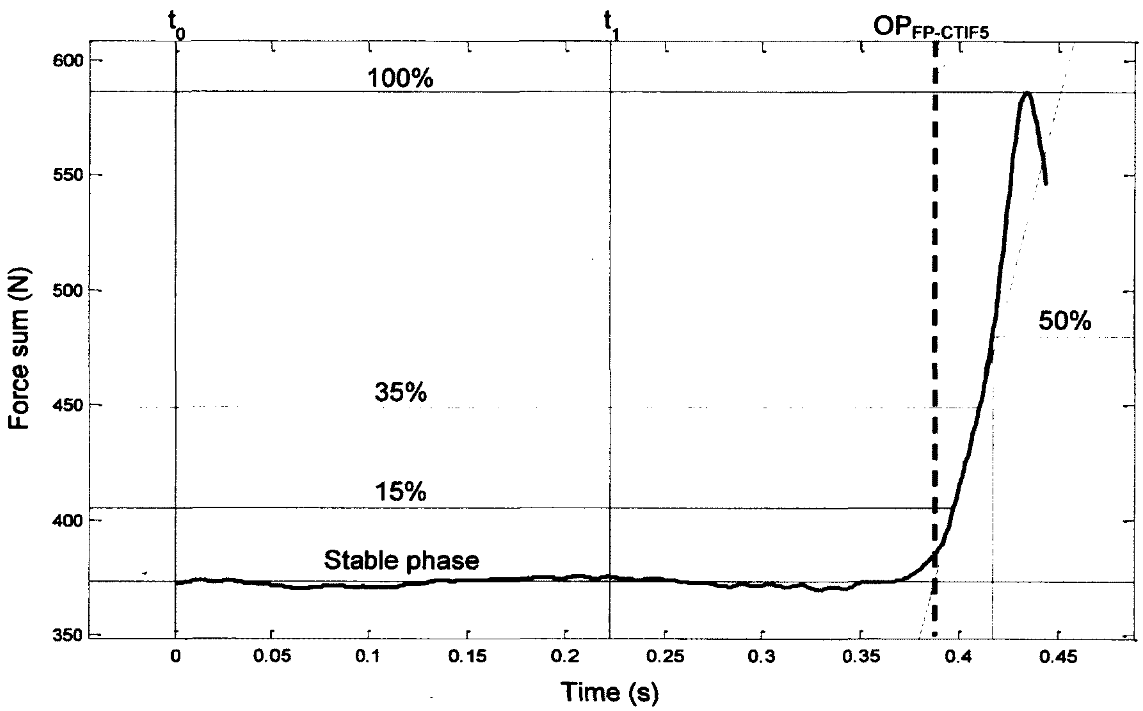

Figure 4.2: The slope interpolation method to identify the onset of perturbation using force plate data ($OP_{FP\text{-}CTIF5}$). The sum of the vertical ground reaction forces shown here is the same as the one shown in the top graph of Figure 4.1 from approximately 200 to 650ms.

The two methods gave results within ±5ms of each other. However, the $OP_{FP\text{-}3SD}$ method was used for the rest of the manual synchronisation, since it was slightly more reliable than the $OP_{FP\text{-}CTIF5}$ method.

The slope interpolation method was also used to identify the onset of perturbation using marker data (OP_{Marker}). Specifically, it was identified as the time point at the intersection of two lines traced on the surface translation velocity (as measured by the marker on the linear motor) from zero to the peak surface translation velocity (Figure 4.3): the horizontal line through the mean value of the surface translation velocity during the stable phase and the line interpolating the surface translation velocity from 15% to 35% of the total amplitude.

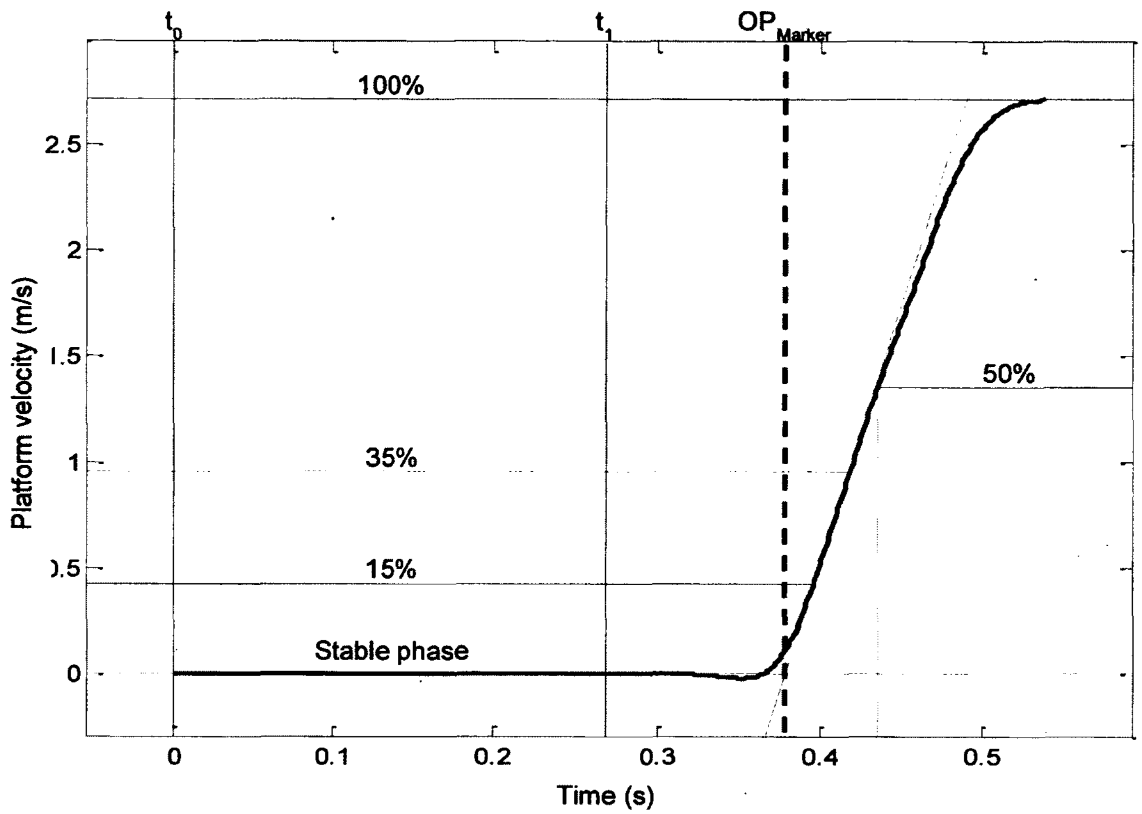

Figure 4.3: The slope interpolation method to identify the onset of perturbation using marker data (OP_{Marker}). The surface translation velocity shown here is the same as the one shown in the bottom graph of Figure 4.1 from approximately 0 to 525ms.

Identifying onset of response (OR)

Onset of response (OR) could only be identified using force plate data and could thus not be used for the manual synchronisation. It occurred when the sum of the vertical ground reaction forces started increasing (at the minimum or at the inflection point, whichever came later) after the onset surface translation but before toe off (Figure 4.1).

Identifying toe off (TO)

Toe off is usually very easily identified using force plate data (TO_{FP}) as the time point when the vertical ground reaction force under the stepping foot becomes zero. However, because of the translation of the rubber sheet, the participant moved from above the small force plate to above the large force plate during the perturbation. More importantly, the presence of the gymnasium mat between the feet and the force plates unfortunately diffused the loads under the stepping and stance foot to both force plates whether the participant was directly above them or not. TO_{FP} could thus only be identified as an inflection time point in the sum of the vertical ground reaction forces (Figure 4.4). As its identification could be affected by user experience, toe off using marker data (TO_{Marker}) was used as a guide.

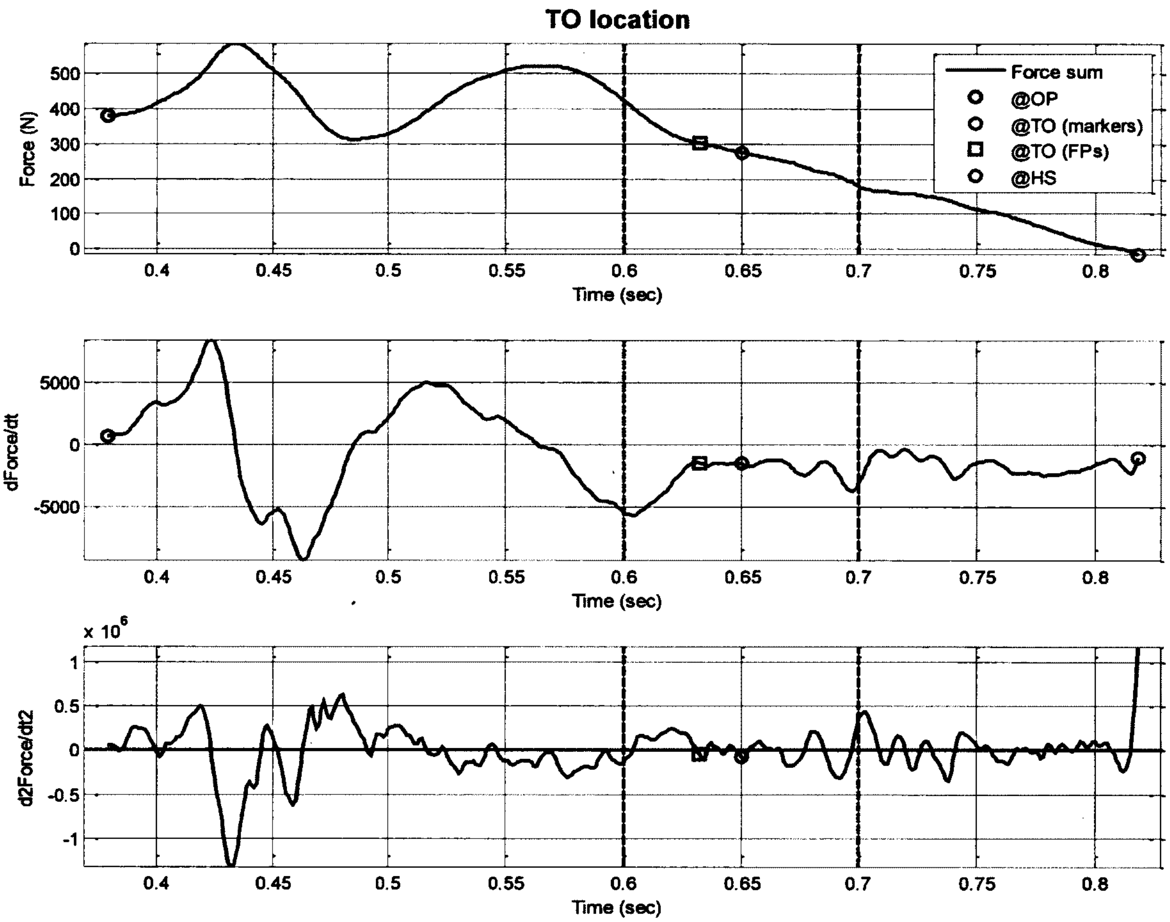

Figure 4.4: The identification of the toe off inflection point on force plate data (TO_{FP}). The sum of the vertical ground reaction forces shown here is the same as the one shown in the top graph of Figure 4.1 from approximately 550 to 1000ms ($OP_{FP\text{-}3SD}$ to HS_{Marker}).

Toe off using marker data (TO_{Marker}) was identified as the time point when the anterior-posterior (y) acceleration of the midpoint of the medial and lateral metatarsals of the stepping foot reached a local minimum (Figure 4.5). This method of identifying toe off using marker data has been previously used by Cyr and Smeesters (2009) with an accuracy of -3±6ms.

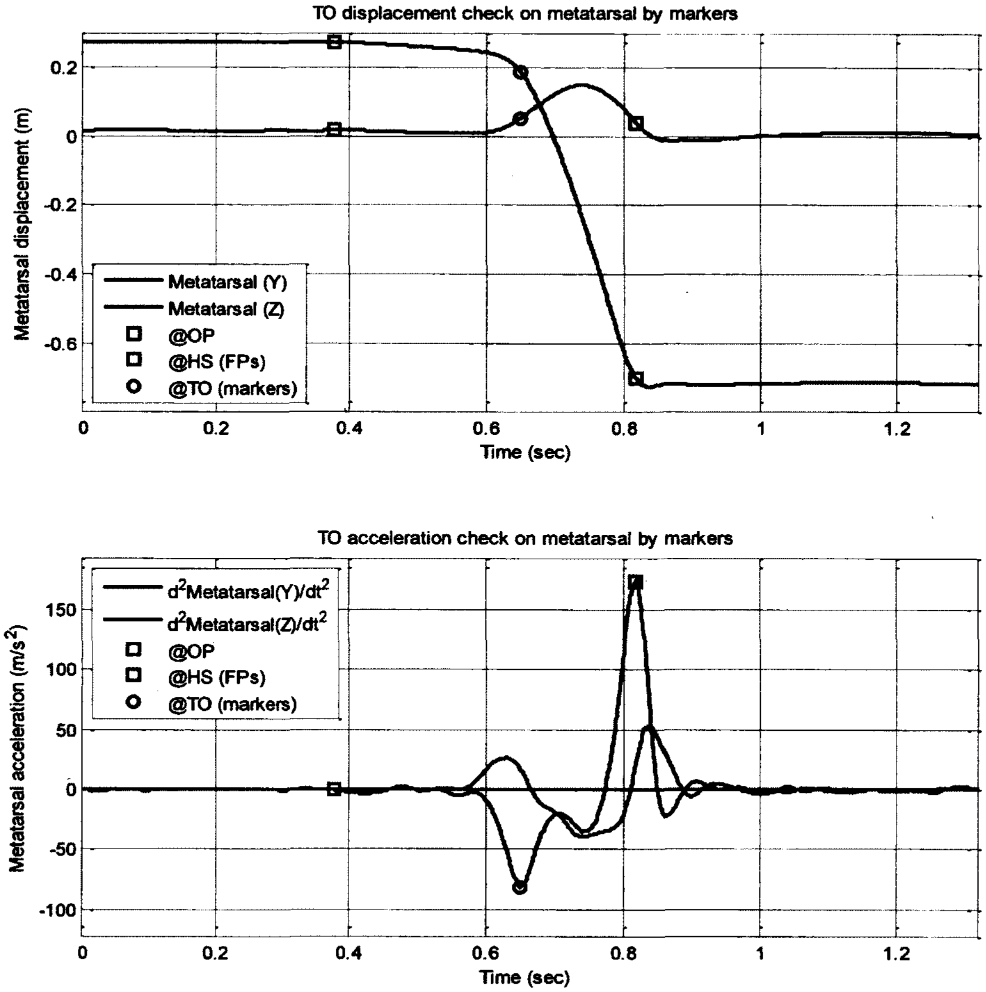

Figure 4.5: The identification of the toe off minimum on marker data (TO_{Marker}). The anterior-posterior (y) and inferior-superior (z) metatarsal displacements and accelerations shown here are for the same participant as the one shown in Figure 4.1.

Identifying heel strike (HS)

Despite the problem of load diffusion due to the presence of the gymnasium mat, heel strike was very easily identified using force plate data (HS_{FP}) as the time point when the sum of the vertical ground reaction forces under the stepping foot started increasing again (Figure 4.6).

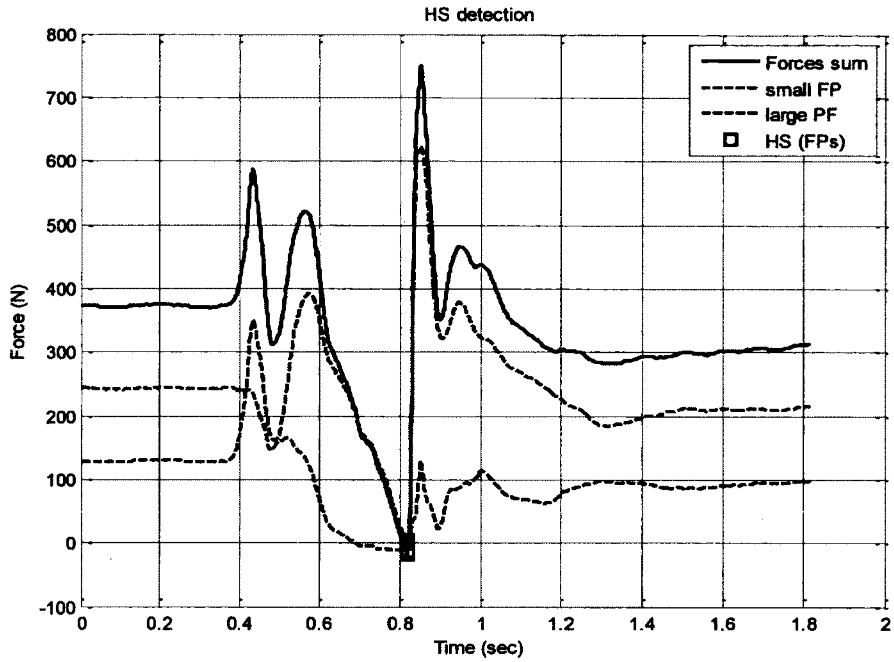

Figure 4.6: The identification of the heel strike impact point on force plate data (HS_{FP}). The sum of the vertical ground reaction forces shown here is the same as the one shown in the top graph of Figure 4.1.

Heel strike using marker data (HS_{Marker}) was identified as the time point when the anterior-posterior (y) acceleration of the midpoint of the medial and lateral malleoli of the stepping foot reached a local maximum (Figure 4.7). This method of identifying heel strike using marker data has been previously used by Cyr and Smeesters (2009) with an accuracy of -10±10ms, using the inferior-superior (z) acceleration of the malleoli. Because of the vertical dissipation of the impact due to the presence of the gymnasium mat, it was found that the anterior-posterior (y) acceleration was more appropriate in this study.

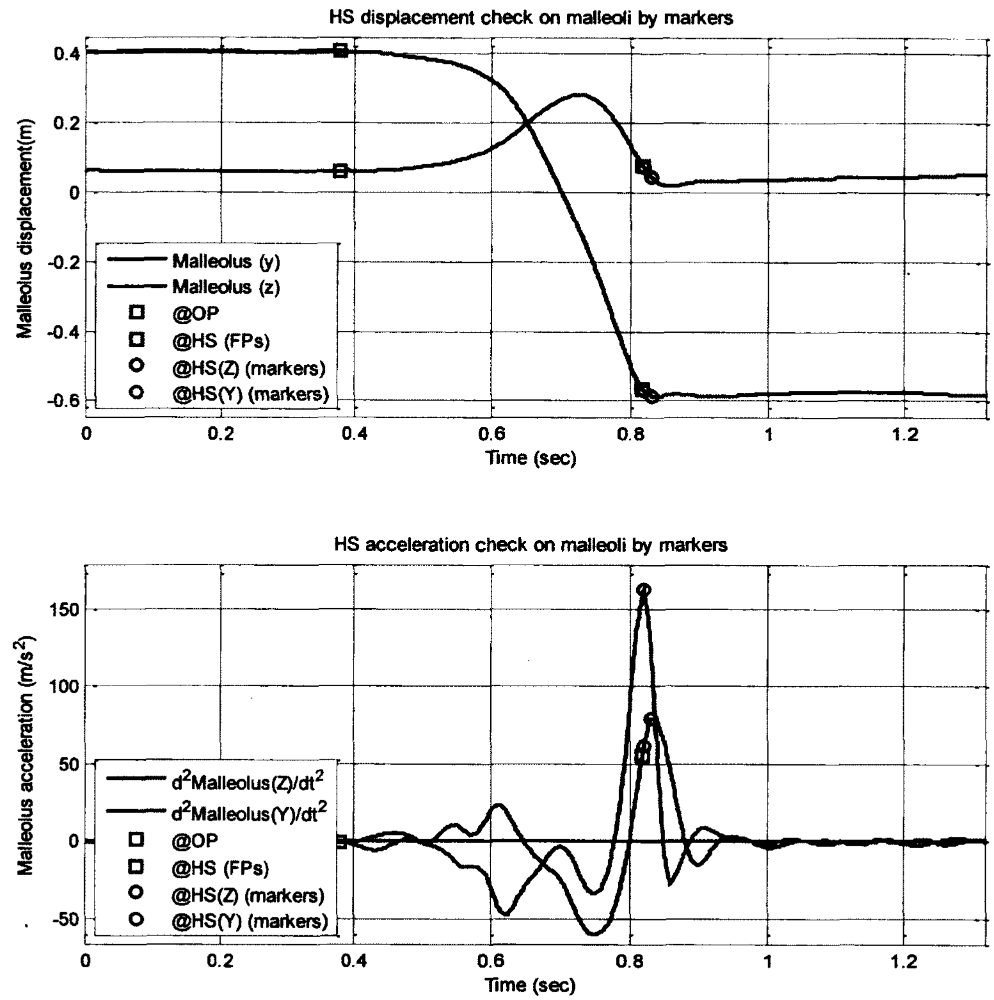

Figure 4.7: The identification of the heel strike maximum on marker data (HS_{Marker}). The anterior-posterior (y) and inferior-superior (z) malleolus displacements and accelerations shown here are for the same participant as the one shown in Figure 4.1.

Synchronising the data

The synchronisation delay at onset of perturbation:

$$\Delta T_{OP} = OP_{FP\text{-}3SD} - OP_{Marker}$$

was on average 47.5±37.9ms and ranged from 12-183ms over the 5 trials analysed for each participant (Table 4.2). Interestingly, the mean synchronisation delay increased as the number of trials increased from 38.5±25.4ms to 58.4±47.4ms. In other words, the synchronisation delays became progressively worse as the experimental session went on.

Table 4.2: Synchronisation delays (ΔT_{OP}) between the onset of perturbation using force plate ($OP_{FP\text{-}3SD}$) and marker (OP_{Marker}) data.

Participant	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5 (max)	Range		Mean delay	Standard deviation
						min	max		
Man 1	26	18	25	33	55	18	55	31.4	14.2
Man 2	103	145	151	173	183	103	183	151.0	31.0
Man 3	46	49	51	47	48	46	51	48.2	1.9
Man 4	18	19	12	13	20	12	20	16.4	3.6
Man 5	21	17	19	21	21	17	21	19.8	1.8
Man 6	46	42	45	45	52	42	52	46.0	3.7
Woman 1	20	16	18	51	43	16	51	29.6	16.2
Woman 2	N/A	18	27	39	45	18	45	32.3	12.1
Woman 3	46	46	120	118	118	46	120	89.6	39.8
Woman 4	N/A	27	21	34	33	21	34	28.8	6.0
Woman 5	37	49	47	56	64	37	64	50.6	10.1
Woman 6	22	32	33	27	19	19	33	26.6	6.1
Min	18	16	12	13	19	**12**		16.4	
Max	103	145	151	173	183		**183**	151.0	
Mean	**38.5**	**39.8**	**47.4**	**54.8**	**58.4**			**47.5**	8.8
SD	**25.4**	**35.6**	**43.5**	**45.7**	**47.4**			**37.9**	

To synchronise the data, we set the onset of perturbation using force plate data ($OP_{FP\text{-}3SD}$) equal to the onset of perturbation using marker data (OP_{Marker}), so that:

$$\Delta T_{OP} = OP_{FP\text{-}3SD} - OP_{Marker} = 0$$

We then verified the accuracy of the synchronisation process by measuring the remaining synchronisation delays at toe off and heel strike:

$$\Delta T_{TO} = TO_{FP} - TO_{Marker}$$

$$\Delta T_{HS} = HS_{FP} - HS_{Marker}$$

On average the remaining synchronisation delays at toe off and heel strike were -8.6±6.1ms and -18.0±9.2ms, respectively, for the maximum surface translation velocity trials (Table 4.3). Given the marker acquisition frequency of 100Hz, toe off and heel strike using marker data (TO_{Marker} and HS_{Marker}) was thus 1 to 2 frames behind toe off and heel strike using force plate data (TO_{FP} and HS_{FP}). Given the vertical dissipations due to the presence of the gymnasium mat, the remaining delays are not surprising. The manual synchronisation thus appears to have been accurate.

Table 4.3: Remaining synchronisation delays at toe off (ΔT_{TO}) and heel strike (ΔT_{HS}) between toe off and heel strike using force plate (TO_{FP} and HS_{FP}) and marker (TO_{Marker} and HS_{Marker}) data after synchronisation at the onset of perturbation.

Participant	OP			TO			HS			Mean
	OP_{Marker}	$OP_{FP\text{-}3SD}$	ΔT_{OP}	TO_{Marker}	TO_{FP}	ΔT_{TO}	HS_{Marker}	HS_{FP}	ΔT_{HS}	$\Delta T_{TO\text{-}HS}$
man 1	193	193	0	451	446	-5	641	640	-1	-3.0
man 2	380	380	0	651	633	-18	821	819	-2	-10.0
man 3	441	441	0	701	695	-6	901	885	-16	-11.0
man 4	620	620	0	911	900	-11	1081	1052	-29	-20.0
man 5	580	580	0	861	851	-10	1051	1031	-20	-15.0
man 6	400	400	0	631	630	-1	811	794	-17	-9.0
woman 1	226	226	0	442	425	-17	601	573	-28	-22.5
woman 2	392	392	0	661	659	-2	841	823	-18	-10.0
woman 3	657	657	0	882	872	-10	1081	1060	-21	-15.5
woman 4	671	671	0	961	955	-6	1170	1146	-24	-15.0
woman 5	267	267	0	511	495	-16	711	698	-13	-14.5
woman 6	480	480	0	750	749	-1	941	914	-27	-14.0
mean			**0.0**			**-8.6**			**-18.0**	**-13.3**
SD			**0.0**			**6.1**			**9.2**	**5.2**

For the remainder of this study, the four critical time points were measured using what we believed was the most accurate and least subjective method:

- Onset of perturbation using the marker on the linear motor (OP_{Marker});
- Onset of response using the vertical ground reaction forces (OR);
- Toe off using the metatarsal markers (TO_{Marker});
- Heel strike using the vertical ground reaction forces (HS_{FP}).

4.1.3 Synchronization impact tests

In a last effort to try and identify the source of the synchronisation delays, a series of impact tests were performed. To do so, the second experimental setup listed in Table 4.1 was used including two electromyography signals at 2000Hz, all six signals from both the large and small force plates at 2000Hz, and twenty-six markers at 125Hz. In particular, three markers were placed on a rubber mallet (Figure 4.8) which was used to create impacts in an alternating fashion on the large and small force plates. These 10-16s impact tests were done both with the linear motor completely off and with the linear motor on using three surface translation velocities between 0.5 and 2.5m/s, with 3 repetitions at each surface translation velocity.

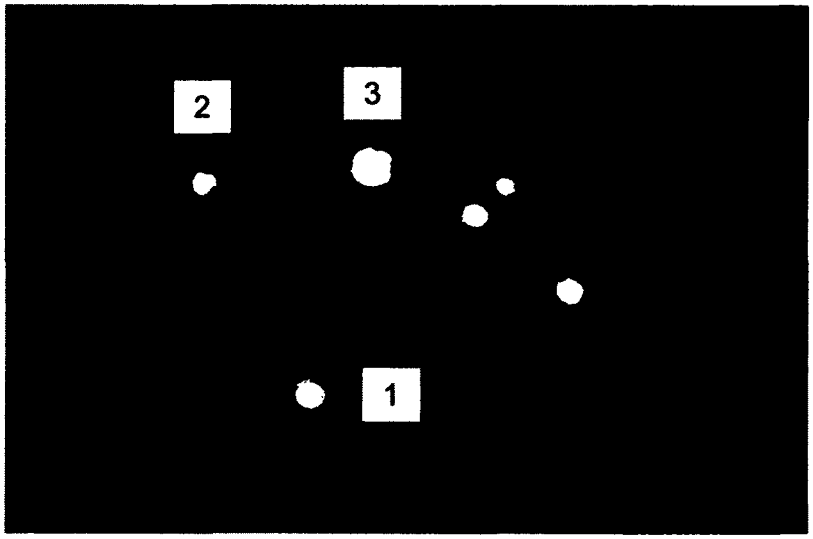

Figure 4.8: The three markers on the rubber mallet used for the synchronisation impact tests.

Despite the large quantity of data acquired, the synchronisation delays between the impacts using the force plate and marker data was always between 2 to 4ms, whether the linear motor was on or not at any velocity (Figure 4.9). Why then were we experiencing synchronisation delays during the surface translations?

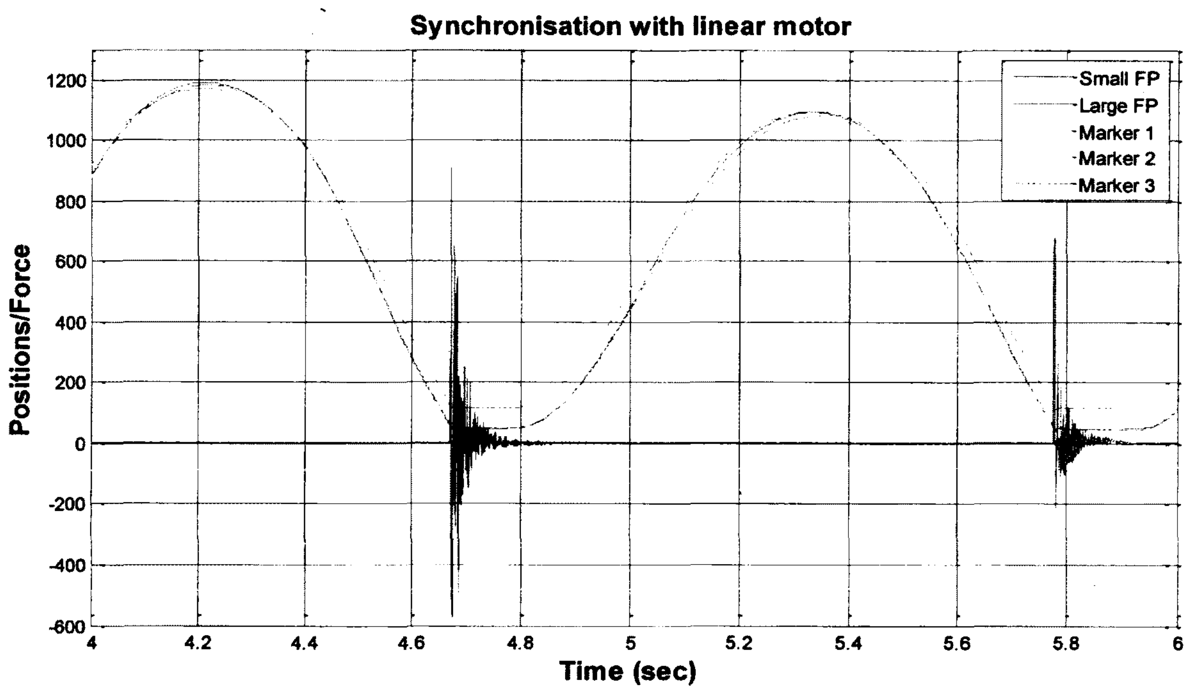

Figure 4.9: Force plate and marker data during two impacts on the large and small force plates with the linear motor at 2.5m/s.

The only significant difference between this impact test setup and the experimental setup was the absence or presence of the gymnasium mat and rubber sheet over the force plates, respectively. Could the rubber sheet translating over the mattress generate some static charge that could affect data collection? Could this static charge accumulate over time and be the source of the synchronisation delays by perhaps increasing or decreasing the amplitude of the synchronisation pulse beyond the required triggering threshold? This seems like a reasonable hypothesis given that no synchronisation delays were experienced during the lean releases when the rubber sheet remained in the same position and the large number of small static shocks sustained during the surface translations by the experimenters.

4.1.4 Initial lean angle calculation

The angular position (θ) was usually measured as the sagittal plane angle between the vertical and the line connecting the midpoints of the medial and lateral malleoli of the stance foot and the two greater trochanters. However, at the onset of perturbation, the angular position or initial lean angle (θ_o) was measured as the sagittal plane angle between the vertical and the line connecting the midpoints of the 4 malleoli (medial and lateral of the stance and step feet) and the two greater trochanters. As the difference between the two ways of measuring the angular position was negligible prior to lean release, it was not explicitly mentioned in the experimental publication (Chapter 2).

4.1.5 Impact of the postural perturbation amplitude on when the surface translation ends and when heel strike occurs

As the surface translation velocity increased in 0.25m/s increments, the width of the $\pm 25 m/s^2$ acceleration and deceleration impulses increased but the time between them (or the duration of the 700mm translation) decreases (Figure 4.10). For several of the trials before the threshold of balance recovery, heel strike thus occurred before the end of the surface translation.

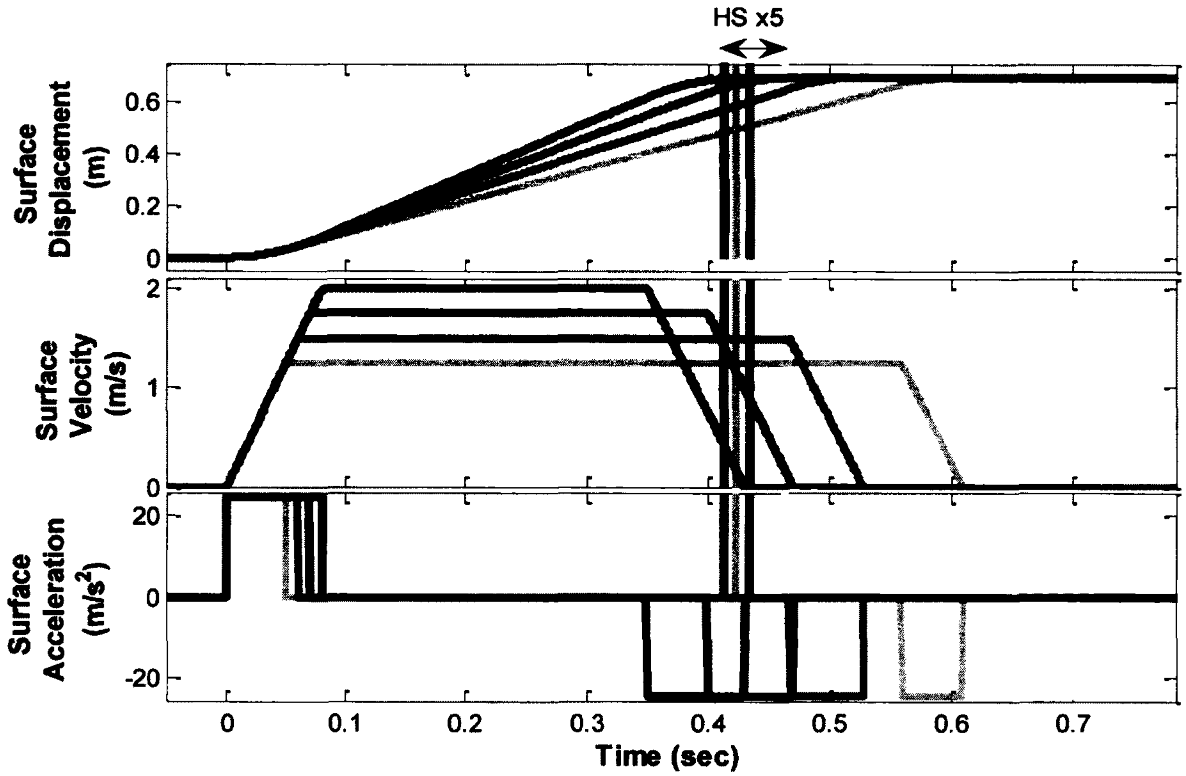

Figure 4.10: Surface translation displacement, velocity and acceleration time histories for all the trials before the threshold of balance recovery for participant 4, from 1 to 2 m/s surface translation velocity. The maximum surface translation velocity of participant 4 was 2.25m/s. Heel strike times (HS) are also shown.

However, at the maximum surface translation velocity, heel strike occurred after the end of the surface translation for all but three participants (Figure 4.11). However, the time between heel strike and the end of surface translation for these three participants was always less than 50ms and thus well into the deceleration impulse. Moreover, while the acceleration impulse was very noticeable to all participants, few noticed the deceleration impulse.

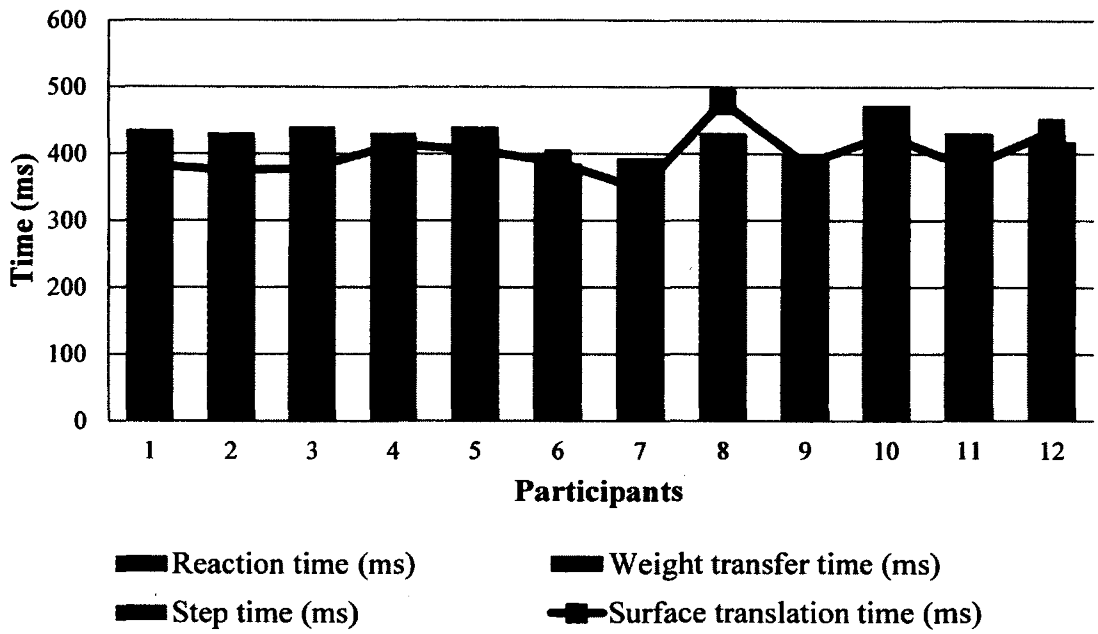

Figure 4.11: Heel strike time, the sum of reaction time, weight transfer time and step time, occurred after the end of surface translation for all but three participants (red squares) at the maximum surface translation velocity.

4.1.6 Rubber sheet strain and stance foot displacement on rubber sheet

During surface translation, the rubber sheet experienced a 5-10% strain (35-70mm stretch / 700mm surface translation). This was measured by the change in the relative anterior-posterior distance between the markers on the linear motor and rubber sheet from onset of perturbation to heel strike (Figure 4.12). Most of the initial stretching happened between onset of perturbation and onset of response while the surface was accelerating (point 1). A local maximum occurred between onset of response and toe off during weight transfer time, while the surface translation velocity remained constant (point 2). Finally, the rubber sheet returned to its initial state between toe off and heel strike while the surface was decelerating (point 3). Negative strain even occurred at the very end of the step sometimes as the stance foot plantar flexed and pushed the rubber sheet backward. Interestingly, rubber sheet strain decreased as maximum surface translation velocity increased.

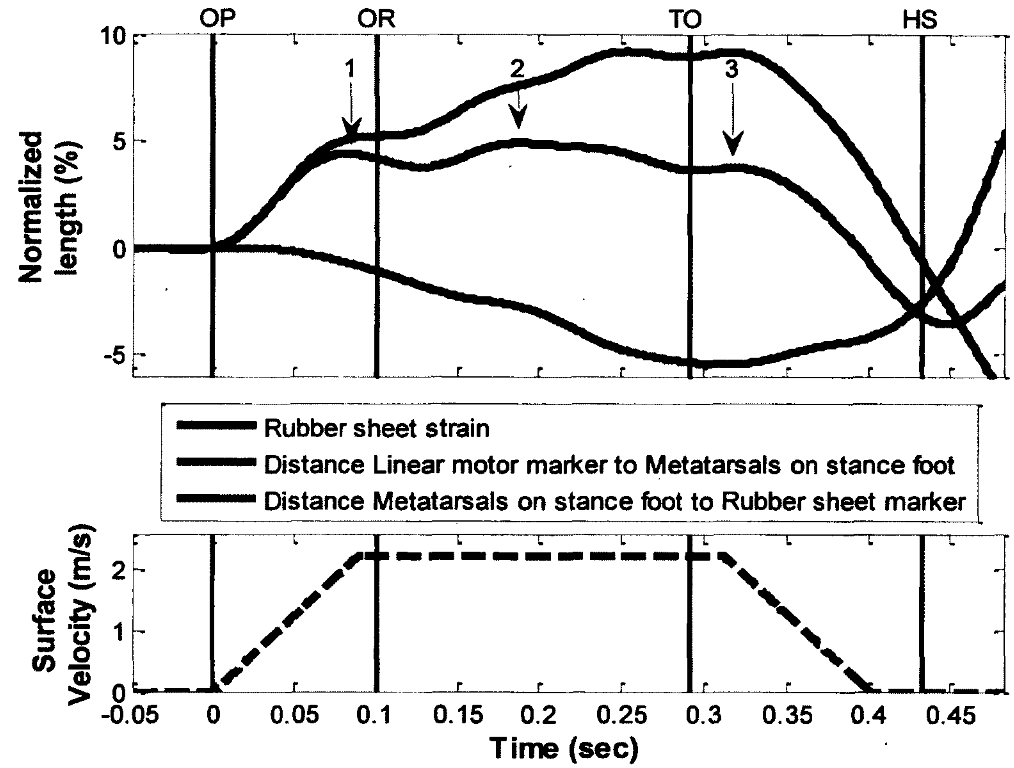

Figure 4.12: Rubber sheet strain over time. OP: onset of perturbation, OR: onset of response, TO: toe off, HS: Heel strike.

Even though the stance foot technically acted like a pivot, it does slightly move relative to the rubber sheet by approximately 5% (35mm displacement / 700mm surface translation) as it plantar flexed. This was measured by the change in the relative anterior-posterior distance between the stance foot metatarsal markers and the markers on the linear motor and rubber sheet from onset of perturbation to heel strike (Figure 4.12). However, it did ultimately return to its initial position at heel strike, so it did not appear that the stance foot was slipping as surface translation occurred. This thus gives some credibility to the fixed pivot point in the inverted pendulum on a skid model.

4.2 Theoretical discussion

4.2.1 Heights of participants

The height of the inverted pendulum on a skid model was adjusted to each participant simulated. As the height of each participant (*h*) was not measured, it was estimated from anthropometric tables as the distance between the midpoints of the 4 malleoli (medial and lateral of the stance and step feet) and the two greater trochanters (Δd) divided by 0.491 (Winter, 2005):

$$h = \Delta d / 0.491$$

As reported in the theoretical publication (Chapter 3), this estimation of the heights of participants did not appear to affect the accuracy of our inverted pendulum on a skid model.

4.2.2 Masses of participants

The mass of the inverted pendulum on a skid model was also adjusted to each participant simulated. Unfortunately, the presence of the gymnasium mat between the feet and the force plates diffused the loads under the feet, not only to the two force plates but also to part of the floor surface. Therefore, despite the fact that a statically standing trial was obtained for each participant a direct measurement of the masses of participants (*m*) was not achieved. In fact, the masses of participants recorded by the force plates in these trials were greatly underestimated (Figure 4.13). Fortunately, it was possible to contact eight of the twelve participants post-experiment and obtain their self-reported masses. The remaining 4 participant masses were thus calculated from the linear regression between the masses recorded by the force plates and the masses self-reported by the participants. As reported in the theoretical publication (Chapter 3), this estimation of the masses of participants did not appear to affect the accuracy of our inverted pendulum on a skid model.

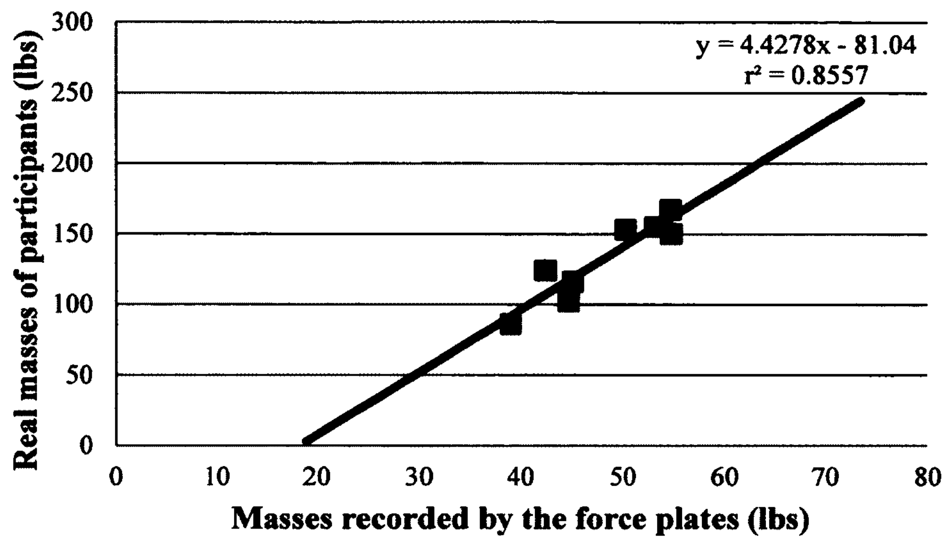

Figure 4.13: Linear regression between masses recorded by the force plates and real masses self-reported by the participants.

4.3 References

Cyr, M. A., Smeesters, C., 2009. Kinematics of the threshold of balance recovery are not affected by instructions limiting the number of steps in younger adults. Gait & posture 29(4), 628-633.

Winter, D. A., 2005. Biomechanics and motor control of human movement. John Wiley & Sons, Hoboken NJ.

CHAPTER 5 CONCLUSION

5.1 Summary of findings

The overall objective of this master's thesis, to determine if balance recovery is possible or if a fall is unavoidable for lean releases and surface translations at the threshold of balance recovery, has thus been achieved. On the experimental side:

- A maximum forward initial lean angle of θ_{max}=27.3±4.8deg and a maximum backward surface translation velocity of V_{max}=2.42±0.36m/s from which younger adults could be suddenly released or pulled, respectively, and still recover balance using a single step were determined. In particular this is the first determination of the maximum surface translation velocity in younger adults.
- The angular positions and velocities at the end of reaction time for lean release and surface translation trials at the threshold of balance recovery formed a perturbation threshold line similar to the one obtained by Moglo and Smeesters (2005) using lean releases, lean releases with pulls and pulls while walking. Unfortunately, the addition of surface translations did not fill in the gap in data points between 80-120deg/s and 10-20deg in the perturbation threshold line.
- Although response initiation variables for the maximum lean angle and maximum translation velocity trials were not significantly different between the two postural perturbations, response execution and geometry variables were significantly different. However, the latter results could have been affected by our experimental setup and should be validated in future experiments.

Furthermore, on the theoretical side:

- A two-dimensional thin rod inverted pendulum model mounted on a horizontally moving skid did accurately simulate the angular position and velocity of participants from onset of perturbation to onset of response for both lean releases and surface translations. In particular, the errors at the end of reaction time were less than 5%.

- Our modeling efforts indicate that it should be possible to fill the gap in the perturbation threshold line mentioned above by using combined lean release and surface translation perturbations or surface translations while walking.

We have thus made some serious advances in pursuing the work by Moglo and Smeesters (2005; 2006) and Smeesters (2009) on the dimensionless perturbation threshold line method, which separates falls from recoveries regardless of the postural perturbation. Being able to compare results across postural perturbations and simulate them using the inverted pendulum on a skid model should therefore help researchers make faster and broader conclusions about balance recovery abilities and thus make these results more readily available to clinicians for fall prevention and rehabilitation.

5.2 Recommendations for future studies

With the experience gained from this master's thesis, the following recommendations in no particular order have been assembled to facilitate future experimental and theoretical studies:

- To insure accurate modeling, heights and masses of participants should be measured.
- Also to insure accurate modeling, rubber sheet pull forces should be measured using a load cell between the rubber sheet and the moving carriage assembly of the linear motor.
- To avoid manual post processing synchronisation, resolve any synchronisation problems.
- To improve ground reaction floor measurements, remove the gymnasium mat and use only the safety harness to insure participant safety.
- To reduce the force required of the linear motor, attempts should be made to reduce the coefficient of friction between the rubber sheet and the floor or gymnasium mat.
- Purchase a more powerful linear motor so as to achieve surface translation velocities of 3m/s or higher with a 700mm displacement and 25m/s^2 acceleration. To be able to do so even with the heaviest participants, the inverted pendulum on a skid model predicts pull forces of 2000-3000N.
- To fill the gap in the perturbation threshold line mentioned above, combine lean release and surface translation perturbations or surface translations while walking.
- Consider exploring backward, sideways and forward maximum surface translation velocities, which would result in forward, sideways and backward losses of balance.

- Increase sample size and add age groups, to strengthen statistical analyses and look into age and gender effects.
- To reduce learning effects and predictability, consider the possibility of randomising the order of postural perturbation amplitudes instead of gradually increasing them. This may however be difficult to do without increasing participant fatigue especially if two or three repetitions are required.
- To reduce learning effects and predictability, consider the possibility of randomising the type and direction of postural perturbations as done by Mansfield and Maki (2009) with pulls and surface translations while standing and walking in place in multiple directions. However, this may not only be difficult to do without increasing participant fatigue, especially if two or three repetitions are required, but may also be technically difficult to do, thus incurring additional experimental costs.

5.3 References

Mansfield, A., Maki, B. E., 2009. Are age-related impairments in change-in-support balance reactions dependent on the method of balance perturbation? Journal of Biomechanics 42(8), 1023-1031.

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Moglo, K. E., Smeesters, C., 2006. Effect of age and the nature of the postural perturbation on the threshold of balance recovery. 30th Annual Meeting of the American Society of Biomechanics, Blacksburg VA, September 6-9.

Smeesters, C., 2009. Theoretically predicting the disturbance threshold line separating falls from recoveries. Dynamic Walking 2009, Burnaby BC, Jun 8-11.

APPENDIX A INVERTED PENDULUM ON A SKID MODEL EQUATIONS

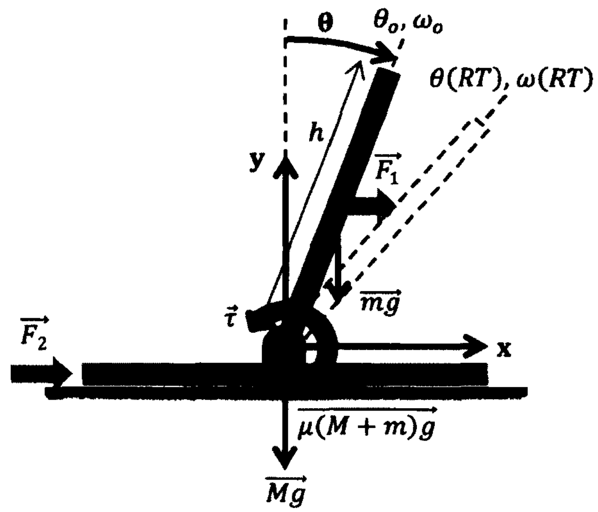

Figure A.1: Inverted pendulum on a skid model

A.1 Hypotheses

- The participant is modelled as a thin rigid rod rotating at the ankles ($I_o = mh^2/12$).
- There is no relative displacement between the ankle of the stance foot and the rubber sheet.
- Motion is limited to the sagittal plane.

A.2 Inputs

- m: participant mass (kg)
- M: skid mass (kg)
- h: participant height (m)
- g: gravity (9.81m/s^2)
- $\vec{F_1}(t)$: waist pull force (N)
- $\vec{F_2}(t)$: rubber sheet pull force (N)
- μ: coefficient of friction between the rubber sheet and mat
- $\vec{\tau}(t)$: ankle torque (Nm)

A.3 Outputs

- $\theta(t) = 90 - \beta(t)$: angular positions (deg)
- $\omega(t)$ or $\dot{\theta}(t)$: angular velocities (deg/s)
- $\alpha(t)$ or $\ddot{\theta}(t)$: angular accelerations (deg/s^2)
- $x(t)$: translational positions (m)
- $\dot{x}(t)$ or $v(t)$: translational velocities (m/s)
- $\ddot{x}(t)$ or $a(t)$: translational accelerations (m/s^2)

… from onset of perturbation at *t*=0 to onset of response at reaction time (*RT*).

A.4 Initial conditions

At *t*=0…

- $\theta_o = 90 - \beta_o$
- $\omega_o = -\dot{\beta}_o = 2v_{walk}/h$
- $x_o = 0$
- $\dot{x}_o = v_o = 0$

A.5 Lagrangian

$$L = \frac{1}{2}\sum_i m_i v_i^2 + \frac{1}{2}\sum_i I_i \omega_i^2 - \sum_i m_i g h_i \qquad \text{B.1}$$

For the inverted pendulum on a skid model…

$$L = \frac{1}{2}Mv_{rubber\ sheet}^2 + \frac{1}{2}mv_{participant}^2 + \frac{1}{2}I_o\dot{\beta}^2 - mg\frac{h}{2}\sin\beta \qquad \text{B.2}$$

$$L = \frac{1}{2}Mv_{rubber\ sheet}^2 + \frac{1}{2}mv_{participant}^2 + \frac{1}{24}mh^2\dot{\beta}^2 - mg\frac{h}{2}\sin\beta \qquad \text{B.3}$$

where…

$$v_{rubber\ sheet}^2 = \dot{x}^2 \qquad \text{B.4}$$

and…

$$v_{participant}^2 = \left(\frac{d}{dt}\left(x + \frac{h}{2}\cos\beta\right)\right)^2 + \left(\frac{d}{dt}\left(\frac{h}{2}\sin\beta\right)\right)^2 \qquad \text{B.5}$$

$$v_{participant}^2 = \left(\dot{x} - \frac{h}{2}\dot{\beta}\sin\beta\right)^2 + \left(\frac{h}{2}\dot{\beta}\cos\beta\right)^2 \qquad \text{B.6}$$

$$v_{participant}^2 = \dot{x}^2 - h\dot{x}\dot{\beta}\sin\beta + \frac{h^2}{4}\dot{\beta}^2(\sin\beta)^2 + \frac{h^2}{4}\dot{\beta}^2(\cos\beta)^2 \qquad \text{B.7}$$

$$v_{participant}^2 = \dot{x}^2 - h\dot{x}\dot{\beta}\sin\beta + \frac{h^2}{4}\dot{\beta}^2 \qquad \text{B.8}$$

Substituting B.4 and B.8 into B.3…

$$L = \frac{1}{2}M\dot{x}^2 + \frac{1}{2}m\dot{x}^2 - \frac{1}{2}mh\dot{x}\dot{\beta}\sin\beta + \frac{1}{2}m\frac{h^2}{4}\dot{\beta}^2 + \frac{1}{24}mh^2\dot{\beta}^2 - mg\frac{h}{2}\sin\beta \qquad \text{B.9}$$

$$\boxed{L = \frac{1}{2}(M+m)\dot{x}^2 - \frac{1}{2}mh\dot{x}\dot{\beta}\sin\beta + \frac{1}{6}mh^2\dot{\beta}^2 - \frac{1}{2}mgh\sin\beta} \qquad \text{B.10}$$

A.6 Equations of motion

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = F_i \qquad \text{B.11}$$

Using B.10, the equation of motion along the x axis is…

$$\begin{aligned} &\frac{d}{dt}\left(\frac{\partial}{\partial \dot{x}}\left(\frac{1}{2}(M+m)\dot{x}^2 - \frac{1}{2}mh\dot{x}\dot{\beta}\sin\beta + \frac{1}{6}mh^2\dot{\beta}^2 - \frac{1}{2}mgh\sin\beta\right)\right) \\ &\quad - \frac{\partial}{\partial x}\left(\frac{1}{2}(M+m)\dot{x}^2 - \frac{1}{2}mh\dot{x}\dot{\beta}\sin\beta + \frac{1}{6}mh^2\dot{\beta}^2 - \frac{1}{2}mgh\sin\beta\right) \\ &\quad = F_1 + F_2 + \mu(M+m)g \end{aligned} \qquad \text{B.12}$$

$$\frac{d}{dt}\left((M+m)\dot{x} - \frac{1}{2}mh\dot{\beta}\sin\beta\right) = F_1 + F_2 + \mu(M+m)g \qquad \text{B.13}$$

$$(M+m)\ddot{x} - \frac{1}{2}mh\ddot{\beta}\sin\beta - \frac{1}{2}mh\dot{\beta}^2\cos\beta = F_1 + F_2 + \mu(M+m)g \qquad \text{B.14}$$

Substituting $\beta = 90 - \theta$ into B.14…

$$\boxed{(M+m)\ddot{x} + \frac{1}{2}mh\ddot{\theta}\cos\theta - \frac{1}{2}mh\dot{\theta}^2\sin\theta = F_1 + F_2 + \mu(M+m)g} \qquad \text{B.15}$$

Using B.10, the equation of motion around the angle β is…

$$\frac{d}{dt}\left(\frac{\partial}{\partial\dot{\beta}}\left(\frac{1}{2}(M+m)\dot{x}^2-\frac{1}{2}mh\dot{x}\dot{\beta}\sin\beta+\frac{1}{6}mh^2\dot{\beta}^2-\frac{1}{2}mgh\sin\beta\right)\right)$$
$$-\frac{\partial}{\partial\beta}\left(\frac{1}{2}(M+m)\dot{x}^2-\frac{1}{2}mh\dot{x}\dot{\beta}\sin\beta+\frac{1}{6}mh^2\dot{\beta}^2-\frac{1}{2}mgh\sin\beta\right)$$
$$=\tau-F_1\frac{h}{2}\sin\beta \qquad \text{B.16}$$

$$\frac{d}{dt}\left(-\frac{1}{2}mh\dot{x}\sin\beta+\frac{1}{3}mh^2\dot{\beta}\right)+\frac{1}{2}mh\dot{x}\dot{\beta}\cos\beta+\frac{1}{2}mgh\cos\beta=\tau-\frac{1}{2}F_1h\sin\beta \qquad \text{B.17}$$

$$-\frac{1}{2}mh\ddot{x}\sin\beta-\frac{1}{2}mh\dot{x}\dot{\beta}\cos\beta+\frac{1}{3}mh^2\ddot{\beta}+\frac{1}{2}mh\dot{x}\dot{\beta}\cos\beta+\frac{1}{2}mgh\cos\beta$$
$$=\tau-\frac{1}{2}F_1h\sin\beta \qquad \text{B.18}$$

$$-\frac{1}{2}mh\ddot{x}\sin\beta+\frac{1}{3}mh^2\ddot{\beta}+\frac{1}{2}mgh\cos\beta=\tau-\frac{1}{2}F_1h\sin\beta \qquad \text{B.19}$$

Substituting $\beta=90-\theta$ into B.19…

$$-\frac{1}{2}mh\ddot{x}\cos\theta-\frac{1}{3}mh^2\ddot{\theta}+\frac{1}{2}mgh\sin\theta=\tau-\frac{1}{2}F_1h\cos\theta \qquad \text{B.20}$$

A.7 Linearization

The resolution of this system of two second order non-linear differential equations (B.15 and B.20) requires linearization into a system of four first order non-linear differential equations where…

$$\begin{aligned} y_1 &= \theta \\ y_2 &= \dot{\theta} \\ y_3 &= x \\ y_4 &= \dot{x} \end{aligned} \qquad \text{B.21}$$

and therefore…

$$\begin{aligned} \dot{y}_1 &= y_2 \\ \dot{y}_2 = \ddot{\theta} &= f(t,y_1,y_2,y_2,y_2) \\ \dot{y}_3 &= y_4 \\ \dot{y}_4 = \ddot{x} &= f(t,y_1,y_2,y_2,y_2) \end{aligned} \qquad \text{B.22}$$

Isolating $\ddot{x}$ in equation B.20…

$$\ddot{x} = \frac{\frac{1}{3}mh^2\ddot{\theta} - \frac{1}{2}mgh\sin\theta + \tau - \frac{1}{2}F_1 h\cos\theta}{-\frac{1}{2}mh\cos\theta} \qquad \text{B.23}$$

$$\ddot{x} = -\frac{2h\ddot{\theta}}{3\cos\theta} + g\tan\theta - \frac{2\tau}{mh\cos\theta} + \frac{F_1}{m} \qquad \text{B.24}$$

Isolating $\ddot{\theta}$ in equation B.20…

$$\ddot{\theta} = \frac{\frac{1}{2}mh\ddot{x}\cos\theta - \frac{1}{2}mgh\sin\theta + \tau - \frac{1}{2}F_1 h\cos\theta}{-\frac{1}{3}mh^2} \qquad \text{B.25}$$

$$\ddot{\theta} = -\frac{3\ddot{x}\cos\theta}{2h} + \frac{3g\sin\theta}{2h} - \frac{3\tau}{mh^2} + \frac{3F_1\cos\theta}{2mh} \qquad \text{B.26}$$

Substituting B.24 into B.15…

$$(M+m)\left(-\frac{2h\ddot{\theta}}{3\cos\theta} + g\tan\theta - \frac{2\tau}{mh\cos\theta} + \frac{F_1}{m}\right) + \frac{1}{2}mh\ddot{\theta}\cos\theta - \frac{1}{2}mh\dot{\theta}^2\sin\theta = F_1 + F_2 + \mu(M+m)g \qquad \text{B.27}$$

$$\ddot{\theta}\left(\frac{1}{2}mh\cos\theta - (M+m)\frac{2h}{3\cos\theta}\right) + (M+m)\left(g\tan\theta - \frac{2\tau}{mh\cos\theta} + \frac{F_1}{m}\right) - \frac{1}{2}mh\dot{\theta}^2\sin\theta = F_1 + F_2 + \mu(M+m)g \qquad \text{B.28}$$

$$\ddot{\theta} = \left(-(M+m)\left(g\tan\theta - \frac{2\tau}{mh\cos\theta} + \frac{F_1}{m}\right) + \frac{1}{2}mh\dot{\theta}^2\sin\theta + F_1 + F_2 + \mu(M+m)g\right) * \left(\frac{1}{2}mh\cos\theta - (M+m)\frac{2h}{3\cos\theta}\right)^{-1} \qquad \text{B.29}$$

Substituting B.26 into B.15…

$$(M+m)\ddot{x} + \frac{1}{2}mh\cos\theta\left(-\frac{3\ddot{x}\cos\theta}{2h} + \frac{3g\sin\theta}{2h} - \frac{3\tau}{mh^2} + \frac{3F_1\cos\theta}{2mh}\right) - \frac{1}{2}mh\dot{\theta}^2\sin\theta = F_1 + F_2 + \mu(M+m)g \qquad \text{B.30}$$

$$\ddot{x}\left((M+m)-\frac{3}{4}m(\cos\theta)^2\right)+\frac{1}{2}m\cos\theta\left(\frac{3g\sin\theta}{2}-\frac{3\tau}{mh}+\frac{3F_1\cos\theta}{2m}\right) -\frac{1}{2}mh\dot{\theta}^2\sin\theta = F_1+F_2+\mu(M+m)g \qquad \text{B.31}$$

$$\ddot{x}=\left(-\frac{1}{2}m\cos\theta\left(\frac{3g\sin\theta}{2}-\frac{3\tau}{mh}+\frac{3F_1\cos\theta}{2m}\right)+\frac{1}{2}mh\dot{\theta}^2\sin\theta+F_1+F_2+\mu(M+m)g\right)*\left((M+m)-\frac{3}{4}m(\cos\theta)^2\right)^{-1} \qquad \text{B.32}$$