TRANSITION BETWEEN SINGLE AND MULTIPLE STEPPING STRATEGIES IN FORWARD FALL RECOVERY

BY

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Submitted to the graduate program in Mechanical
Engineering and the Graduate Faculty of the University of
Kansas in partial fulfillment of the requirements for the
degree of Master's of Science

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Abstract

Background. Following a balance disturbance, one or more steps are often taken. Studies have shown that older adults are more likely than young adults to take multiple steps, and that number of steps is a predictor of fall risk. In order to better understand how a stepping strategy is chosen, we investigated the transition between single and multiple stepping strategies in young adults.

Methods. Each participant responded to a sudden release from an initial forward lean. We limited available first step length with a visible boundary line to induce transitions between single and multiple stepping strategies. The available step length where the transition occurred (transition threshold) and the biomechanics of the first step on either side of the transition were quantified in terms of temporal, kinematic, and kinetic parameters.

Results. The magnitude of the transition threshold displayed hysteresis sensitive to direction of the transition (single to multiple steps versus multiple to single steps). Step liftoff, swing, and landing times, step length, step length boundary margin, and braking forces during landing were different on either side of the transition.

Discussion. If transition threshold is used as a clinical measure, the method used to detect the threshold should be further studied. More sophisticated threshold detection protocols may minimize hysteresis. Biomechanical changes in the first step suggest that the second step is planned before liftoff of the first step, rather than only after failure of the first step to recover balance.

Acknowledgements

I would like to express gratitude to my advisor, Dr. Carl Luchies, for his encouragement and guidance during my tenure as a graduate student. His academic expertise on research and personal perspective on life were invaluable to me through the ups and downs of the research experience. I would also like to thank my committee members, Dr. Lorin Maletsky and Dr. Sara Wilson, for their support.

I wish to acknowledge the extensive technical and moral support I have received from Molly McVey and Sommer Amundsen. I could not have asked for two better co-investigators, test subjects, therapists, lab mates, and friends. I also owe a debt of gratitude to Dr. Antonis Styianou for lending his voice of experience and reason. I would also like to thank Charles Gabel and Ron Schorr, whose mechanical and technical expertise were invaluable in making this project possible.

Finally, I would like to sincerely thank all of my friends and family who have stood by me during this journey. The continuing optimism and encouragement of my mom, dad, and sister has been more valuable than I often admit. I would also like to thank my good friends Scott and Dieter for seeing me through the final stages of this project and helping me take some much-needed diversions from academics.

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CHAPTER ONE: INTRODUCTION

Motivation

Falls accounted for 2.6 million injuries requiring treatment and 10,300 deaths in 2000 in the United States [1]. The total estimated cost of these falls has been estimated to total over 19 billion dollars. Besides physical injury, experiencing a fall often leads to loss of confidence and fear of falling [2]. Fear of falling is associated with decreased activity levels and poorer mental health [3-5]. Fall risk depends on an individual's ability to both avoid balance disturbances and recover balance when a disturbance has occurred [6]. Understanding the mechanisms of balance recovery following a balance disturbance is therefore crucial to developing diagnostic techniques and interventions to prevent falls.

Background

When a balance disturbance is encountered, one or more steps are often taken [7]. The step response consists of preparation and execution phases [8]. During the preparation phase, anticipatory postural adjustments may move the center of mass toward the stance limb prior to unloading of the step limb [9]. During execution phase, the step foot advances to reconfigure the base of support and restore balance.

The ability to recover balance using a single step has been shown to associate with both the length and speed of the step [10, 11]. Furthermore, it has been demonstrated both experimentally and theoretically that as disturbance magnitude is increased, a larger step is required [12-14]. A multiple step response, however, can be used to reconfigure the base of support beyond the position of the first stepping foot. Older adults have been shown to take multiple steps more often than young and to transition from a single to multiple step strategy as disturbance magnitude is increased [15, 16]. Furthermore, number of steps taken has been shown to be predictive of future fall risk [17]. While the transition from no steps (sway strategy) to a stepping strategy has been studied [6, 18], the conditions for and biomechanical costs of the transition between single and multiple step strategies are not known. Since the ability to recover balance using a single step has been shown to depend on the length of the first step [14, 11], limiting the available first step length may allow researchers to induce a transition between single and multiple stepping strategies. The threshold available step length at which the transition occurs would be one way to quantify the transition between stepping strategies. Since the transition threshold between balance recovery strategies may be an effective measure of fall risk, the methods used to determine the transition and the biomechanical costs of the transition need to be better understood.

Specific aims

In this study, we sought to improve understanding of three aspects of the transition between single and multiple steps with the following **research questions**:

(1) How does the transition direction (e.g. single-to-multiple versus multiple-to-single) affect the transition threshold?

(2) What effect do verbal instructions (e.g. take only a single step) have on the transition threshold?

(3) How do the biomechanics of the preparation phase and first step compare on either side of the transition threshold?

We tested the following **hypotheses**:

(1) The transition threshold occurs at a shorter available step length when the transition direction is from single to multiple steps.

(2) Verbal instructions to use only a single step cause the threshold to occur at a shorter available step length.

(3) The biomechanics of the preparation phase and first step are different on either side of the transition threshold.

To test these hypotheses, we asked healthy young participants to recover from a simulated forward fall initiated by a release from an intial static leaning position. We controlled the available length of the first step taken by instructing the participant not to step over a visible boundary line, which was projected, on the floor directly in front of them oriented from left to right. By increasing or decreasing the available length of the first step, we induced a transition between single and multiple stepping strategies, and recorded responses on either side of the transition threshold.

Thesis content

This thesis contains four chapters and an appendix. Chapter one is an introduction to the topic being studied. Chapter two consists of a survey of literature published in the research area being studied. Chapter three consists of a self-contained manuscript describing details of a study investigating the transition between single and multiple step responses during balance recovery. Chapter four is an overall summary of the study, including recommendations for future study.

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CHAPTER TWO: BACKGROUND

Falling

In the United States, non-fatal falls accounted for 2.6 million injuries requiring treatment and 10,300 deaths in 2000 [1]. The total estimated cost of these falls has been estimated to total over 19 billion dollars. Besides physical injury, experiencing a fall often leads to loss of confidence and fear of falling [2]. Fear of falling is associated with lower gait speed, as well as decreased activity levels and poorer mental health [3-5]. Understanding the mechanisms of balance and why some groups of people, especially the elderly, are more prone to falls is crucial in developing diagnostic techniques and interventions to prevent falls.

Biomechanical changes with age

Many biomechanical changes occur as people age, a number of which may be related to increased risk of falling. One such change is decreased strength. This can be manifested as both a decrease in maximal strength of certain muscles, or as a decreased ability to rapidly generate muscle force. Either type of deficit could impair older individuals’ ability to recover balance from a postural disturbance [6]. Another biomechanical change that occurs with age is decreased joint position sense (proprioception). Dynamic ankle position sense is an important input in the postural control feedback loop, and poorer scores on dynamic position sense tests are associated with decreased performance on a balance task [7]. Aging also decreases cutaneous sensitivity on the soles of the feet, and within elderly subjects, decreased cutaneous sensitivity correlates with poorer performance during postural performance following postural perturbations [8]. Incidence of visual impairment also increases with age [9] and is associated with increased fall risk [10].

Types of disturbances

During quiet standing, the human body can be modeled as an inverted pendulum, with a high center of mass being supported by a relatively small base. As such, it is inherently unstable, and forces must be actively manipulated in order to maintain this posture. Maintenance of upright stance involves using joint torques to move the resultant application point (center of pressure) of ground reaction forces in order to keep the projection of the whole body center of mass within the base of support. The center of pressure (COP) can thus be viewed as the control variable that allows the central nervous system to control the location of the center of mass (COM) [11].

In addition to having a position located above the base of support, the COM must also have a horizontal velocity small enough such that it can be brought to rest before its projection onto the plane of the floor moves outside of the boundaries of the base of support [12, 13]. When the COM does move outside of the base of support (or acquires sufficient velocity such that it will inevitably move outside of that base), a response that reconfigures the base of support is the only way to avoid a fall. The base of support can be reconfigured by grasping with the an upper limb or stepping with the lower limb [14]. When a stepping strategy is used, one or more steps may be needed in order to bring the center of gravity to rest within the newly reconfigured base of support. Theoretical limits have been estimated for the size of step necessary to accomplish balance recovery [13, 15].

Both the location and the velocity of the COM with respect to the base of support have been experimentally manipulated in order to observe balance response in the laboratory. Impulsive loads applied at the waist in the posterior [16, 17], anterior [18, 19], or lateral [20, 21] directions perturb balance by providing a sudden change in momentum. In these experiments, participants typically stand in a comfortable, upright position, with a harness or belt around their waist. Attached to the belt is a cable leading to a torque motor or suspended weight. At an unexpected moment, the torque motor is engaged or weight is dropped, requiring the participant to respond in order to maintain balance.

Experiments utilizing these pull methods have several advantages. Prior to administration of the disturbance/pull, the participant is standing in a natural position. This may result in a more realistic response than seen in methods in which the body position is artificially positioned in a leaning position at the beginning of the test. It is also possible to disguise the direction from which the pull will come by attaching multiple tethers to the participant’s waist, but only pulling one of them. One limitation of these methods is that the force that can be safely applied at a participant’s waist defines an upper limit on the magnitude of the balance disturbance.

Others have induced postural perturbations using sudden translations of the support surface on which the participant stands [22]. During each trial, a controlled motor shifts the floor under the participants’ feet according to a predetermined motion profile—typically using a ramped velocity profile. This type of perturbation may allow the least amount of equipment to be attached to the participant, but requires the floor to be heavily instrumented. The duration of floor movement may also have an effect on the step response. In their study using platform translations to induce balance disturbances, McIlroy et al. [23] found that the average contact time during a single forward step response to the platform perturbation was 529ms. The platform movement, however, lasted 600ms. Thus, he suggests that some characteristics of the stepping response may be due to deceleration of the platform, rather than the initial platform acceleration.

A third method used to induce a balance disturbance is sudden release from a static leaning position [24-30]. This is accomplished by attaching a horizontal rope to a waist or chest harness and asking the participant to lean forward or backward until they are supported by the rope. The length of the rope is then adjusted until the desired initial conditions are reached, the rope is released, and the participant responds to the new unstable configuration. The initial conditions are usually specified in terms of percentage of body weight supported by the rope, as measured by a load cell on the rope mount. However, reporting of the initial conditions in each trial is often done in terms of whole body lean angle, which can be computed post-hoc as the angle from vertical of the vector connecting the ankle to acromion process (using a motion measurement system), or as the angle from vertical of a vector connecting the ankle to the center of mass, using a statics analysis that takes into account the both the magnitude of the ground reaction forces and their location relative to the ankle joints [26].

Protocol variations

Testing at set disturbance levels vs. levels determined by performance

Approaches to controlling the magnitude of balance disturbances across a participant population fall into two categories: (1) using a similar level for all participants, or (2) testing at the maximum level at which the participant exhibits a particular type of response. Thus far, studies using platform translations and waist pulls have exclusively used the first approach. Platform translations are usually a fixed set of distances and velocities for all participants. The magnitude and distance of waist pulls are often scaled to the participants' height and weight, and the set of scaled disturbances used are similar across participants [17, 31]. Lean and release studies have used both the first and the second approach. Because of the ease with which the rope length can be adjusted, it is possible to incrementally increase the disturbance magnitude with each trial until the participant takes at least one step [32], more than one step [24, 33], or is no longer able to recover balance [33].

Constraints on number of steps

Varying instructions have been used to prescribe the type of response in lean and release studies. For example, participants have been asked to respond naturally [16, 23], try to keep from falling [23], recover without taking a step [32], recover by taking a single step [25, 33, 34], or by taking no more than two steps [33].

Constraints on step length

Besides being used to characterize participants’ response to a balance perturbation, step length can be constrained during an experiment in order to determine the effects of step length on other variables. In one study, participants were asked to take natural, short, or long steps in order to recover balance [35]. Others have refined this technique and placed a visual target line on the floor using tape. King et al. [25] normalized the taped line’s position between participants by testing at fixed locations relative to the participants’ natural response step length (i.e., the foot landing position when no step length constraint was given.) They tested participants at the same lean angle for all conditions, but with the taped line at the natural step position, as well as 10 cm in front and 10 cm behind it.

Hsiao-Wecksler et al. [24] tested participants with a step length target line at 15%, 25%, and 35% body height in front of the starting position. For each target position, they incrementally increased the initial lean angle in order determine the maximum angle from which the participant could recover without exceeding the step length constraint.

Constraints on step length may be difficult to control, however. In both studies, experimenters discarded trials in which the participant did not comply with step length constraints. For example, King et al. discarded trials post-hoc if the actual step length was not within 5 cm of intended step length, while Hsiao-Wecksler et al. repeated trials when the experimenters noticed that the participant was stepping over the line. Nevertheless, even with these quality controls, trials in which data was analyzed still showed significant step length errors by participants. When King et al. asked participants to step shorter than their natural step length, they exceeded the target line by an average of about 2 cm. Similarly, the young healthy participants in Hsiao-Wecksler et al.'s study exceeded the target line by an average of two or three percent body height, depending on the step length.

Data analysis techniques

Participants' performance on lean and release tasks has been characterized in a variety of ways. Perhaps the most straightforward parameter used is the maximum recoverable disturbance magnitude. This parameter is relatively easy to determine, and gives a good global picture of how well an individual can respond to a large balance disturbance. However, efforts to better differentiate between the balance responses of different participants has led to development of more precise descriptive parameters.

Ground reactions

Since during quiet standing in healthy participants, the body's weight is distributed nearly evenly between the two legs, the net center of pressure is nearly centered in the mediolateral direction. During a step, however, the center of pressure must lie within the area of foot contact under the stance limb. Prior to liftoff, the center of pressure may make a smooth movement from the middle of the base of support, or exhibit an initial lateral shift towards the swing limb. Such a lateral shift, termed an anticipatory postural adjustment (APA) [14], could be used to create a torque about the center of mass, pivoting it towards the eventual stance limb. This would counteract the tendency of the COM to fall laterally towards the swing limb during the step.

APA's have been characterized by their number [36], onset time, amplitude, and duration [18]. Amplitude is defined as the distance that the COP shifts towards the swing limb, and duration is the time over which the shift occurs.

Center of mass

The position and velocity of the projection of the center of mass onto the plane of the floor with respect to the base of support has been used as a measurement of stability. Increased lateral velocity of the center of mass has been interpreted as indicating a threat to balance [37]. While comparing the magnitudes of the position and velocity can be informative, a more refined method of interpreting stability based on this information has been developed. The “extrapolated center of mass” used by Hof et al. [12] is the theoretical displacement which will occur in the center of mass before the velocity can be brought to zero, as predicted by an inverted pendulum model of upright stance. This extrapolated center of mass applied to the COM position and velocity of humans during a balance recovery task has been shown to correlate with whether the participant will take multiple steps to recover balance, i.e. if the extrapolated center of mass is beyond the base of support after a single step, the participant must take another step to prevent falling [38].

Kinematics

Movement of the body segments can be measured using an active (e.g., Optotrak) or passive (e.g., Vicon) motion system. During balance recovery, such measurements allow detailed characterization of step length, foot trajectory, and joint angles. Parameters that can be extracted include step height (important since insufficient foot clearance can lead to tripping), step width, joint range of motion used, and joint configuration at toe-off or heel strike.

Kinetics

By combining kinematic data with foot/floor reaction measurements, equivalent joint torques and forces can be computed using inverse dynamics modeling. The equivalent torques represent the net torque about an approximated joint center generated by all of the muscles spanning the joint. Paired with measurements of the maximum torque that a participant can generate about a given joint in a maximal isometric test, researchers can calculate what percentage of total available net joint torque is being utilized during balance recovery.

Results and findings

Disturbance magnitude

At very small magnitudes, participants may recover from a balance disturbance simply by shifting their center of pressure within the current base of support. This has been termed the "ankle strategy" [32] because torque generated at the ankle arrests the body's destabilizing rotation. At larger magnitudes, participants must take one or multiple steps to regain balance.

When the lean angle is large enough that participants must take one or more steps to regain balance, it has been speculated that the preparation phase (from disturbance to liftoff of the first stepping foot) is invariant with respect to disturbance magnitude

[39], while the stepping and recovery phases can be adapted to compensate for larger disturbances.

Effects of age

Numerous studies have demonstrated that the maximum disturbance magnitude from which balance can be successfully recovered is smaller for older adults than for young adults [24, 26, 27]. This result is similar whether comparing young men to older men or young women to older women.

Luchies et al [17] found significant differences in stepping strategy with age. In response to a backwards pull, young participants typically responded with a single step with step length increasing as disturbance magnitude increased. Older participants, on the other hand, switched from a single step to multiple step strategy without significantly lengthening the length of the first step. This finding is especially interesting viewed in light of a newer study suggesting that taking multiple steps, as opposed to a single step, in response to a lateral pull is a strong predictor of future fall risk [40]. It is possible that older adults utilize the multiple stepping strategy in order to reduce the required joint range of motion, joint torque, or because they perceive taking multiple steps as safer.

When instructed to recover balance using only a single step, older adults take a shorter step than young [17, 38]. Mademli et al. [12] correlate step length with an index of dynamic stability using the difference between the extrapolated center of mass previously mentioned and the anterior edge of the base of support. Since Hof et al.'s [12] inverted pendulum model implies that the ability to recover balance is a function of the speed and distance with which a compensatory step can be taken, the shorter steps taken by older adults may indeed compromise balance.

Speed of the compensatory step may also have an impact on lateral balance. Rogers et al. used the center of mass position and velocity in the lateral direction to describe lateral balance during stepping after a forward pull. He found that while the position and velocity of the center of mass at step liftoff was similar, older adults with a history of falls fell further laterally towards the stepping foot by heel contact [18]. Applying the inverted pendulum model in the lateral direction predicts that slower steps would lead to more lateral COM displacement at heel contact.

Effects of step length

Stepping response to a balance disturbance has been studied at both the chosen "natural" step length and at artificially constrained step lengths. King et al [25] compared characteristics of balance recovery steps in natural, long (natural step length + 10cm) and short (natural step length – 10 cm) steps to a target line on the floor. All tests were carried out at the same disturbance magnitude. They found that while step length affected leg swing time and impulse at landing, the step preparation phase was similar across step lengths in young healthy males. This was interpreted as further evidence that the step preparation phase is not only invariant with respect to disturbance magnitude as previously suggested [39], but also invariant with respect to step length constraints. However, others have found conflicting results, suggesting that reaction time and step liftoff time occur more quickly when the participant perceives a more imminent threat to balance, such as when asked to recover with a very short step [35].

Hsiao-Wecksler et al. [24] did a similar series of tests in which young and old women were instructed to recover balance by stepping to one of three target lines. However, rather than keeping the disturbance magnitude the same across all step lengths, the peak disturbance from which balance could be recovered was used for each step length. They found that both young and old participants could recover from larger disturbances when longer steps were allowed, but that across step lengths younger participants could recover from larger disturbances than old. Interestingly, they found that recovery ability correlated with step contact time, supporting the idea that step length and timing interact to determine recovery ability.

Effects of instruction

In many studies, participants are asked to respond by taking a single step. While this makes the experiments easier to control, it may cause participants to adopt an unnatural strategy, especially since older adults have been shown to prefer to take multiple steps [17]. Additionally, older individuals may choose to violate the single-step instruction or refuse to continue the experiment rather than rely on the safety harness to help them regain balance [26].

Recent work has been done to assess the impact of instructing participants to recover using a single step. Smeesters et al [33], when examining the effect of instructions limiting the number of steps, found that with no restrictions, twenty-two out of twenty-eight healthy young participants used more than one step to recover balance at the maximum disturbance magnitude. They also found that when allowed to take more than one step, participants were able to recover from significantly larger lean angles than when they were restricted to a single step. Participants also took an earlier, longer first step when they were restricted to a single step response [41]. However, biomechanical changes induced by limiting the number of steps were deemed by the authors to be too small to be functionally significant.

The number of steps used to recover has also been shown to be an important parameter. Hillard et al. [40] found that participants who always used multiple steps to recover from a lateral disturbance were 6 times more likely to experience falls than those who did not always use multiple steps. By restricting the number of steps allowed, researchers may be losing a valuable piece of information regarding the participants' preferred strategy.

On the other hand, allowing participants to take multiple steps has disadvantages as well. As pointed out by Cyr et al. [33], allowing only a single step means ground reaction forces of the stepping foot can be measured using a single force plate. They also suggest that if multiple step responses are prohibited, experimenters can intervene to help a participant regain balance as soon as more than one step is taken, increasing safety and comfort of the experiment. From a data analysis perspective, there is also a disadvantage to having to analyze data from two separate responses. If the number of steps taken by a participant affects the step preparation or first step response characteristics, then pooling data from single and multiple-step responses, as is done by McIlroy et al. [23], may introduce errors.

Timing parameters

The time course of recovery of balance following a disturbance can be divided into three phases: step preparation, swing, and recovery stance phases. While it has been suggested by some that the step preparation phase is consistent regardless of disturbance magnitude and step length constraint [25, 39], others have found that increasing disturbance magnitude leads to slightly shorter weight shift times and faster foot liftoff times [26]. Swing time, on the other hand, is longer when bigger steps are taken. When holding step length constant, Hsiao-Wecksler et al. found that the time from disturbance onset to step foot contact was inversely related to the maximum recoverable lean angle [24]. This supports the notion that length and speed are critical characteristics of the recovery step.

Transitions in biomechanical systems

In response to a changing environment, discrete changes occur in the biomechanical modes of locomotion (walking versus running) [42], reaching (forearm pronation versus supination) [43], upright postural control (in-phase versus out of phase ankle and hip rotations) [44], and balance recovery (sway versus single or multiple stepping) [32]. These modes have been described as emergent phenomenon characteristic of a self-organizing nonlinear system [44]. Transitions during locomotion and reaching exhibit both stability (transitions rarely occur without environmental change) and hysteresis (transitions occur at a different stimulus magnitudes depending on the direction of the change). However, the transition between single and multiple stepping during balance recovery has not been studied.

Summary

Falling becomes a significant health risk as people age. However, causes of the age-related decline in balance are not fully understood. Numerous studies have quantified differences between young and old participants' response to a balance disturbance, but often artificially restrict the response by limiting the number of steps. While there has been some investigation into the effect of limiting the number of steps on maximum recovery threshold, similar experiments have not been done at disturbance magnitudes well within the participants' recovery abilities, and the transition between single and multiple stepping strategies has not been described. A study designed to identify how balance response characteristics change as a function of number of steps taken and instructions limiting the number of steps would aid in determining appropriate experimental protocols for evaluating balance recovery and might shed light onto the question of whether step strategy (single versus multiple steps) is preplanned.

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CHAPTER THREE: STUDY MANUSCRIPT

Abstract

Background. Following a balance disturbance, one or more steps are often taken. Studies have shown that older adults are more likely than young adults to take multiple steps, and that number of steps is a predictor of fall risk. In order to better understand how a stepping strategy is chosen, we investigated the transition between single and multiple stepping strategies in young adults.

Methods. Each participant responded from a sudden release from an initial forward lean. We limited available first step length with a visible boundary line to induced transitions between single and multiple stepping strategies. The available step length where the transition occurred and the biomechanics of the first step on either side of the transition were quantified.

Results. The magnitude of the transition threshold displayed hysteresis sensitive to direction of the transition (single to multiple steps versus multiple to single steps.) Step liftoff, swing, and landing times, step length, step length boundary margin, and braking forces during landing were different on either side of the transition.

Interpretation. If transition threshold is used as a clinical measure, the method used to detect the threshold should be further studied. More sophisticated threshold detection protocols may minimize hysteresis. Biomechanical changes in the first step suggest that the second step is planned before liftoff of the first step, rather than only after failure of the first step to recover balance.

1. Introduction

Falls accounted for 2.6 million injuries requiring treatment and 10,300 deaths in 2000, costing over 19 billion dollars [1]. Besides physical injury, falls lead to loss of confidence and fear of falling [2]. Fear of falling is associated with decreased activity levels and poorer mental health [3-5]. Fall risk depends on an individual's ability to both avoid balance disturbances and recover balance when a disturbance has occurred [6]. Understanding the mechanisms of balance recovery is crucial to developing diagnostic techniques and interventions to prevent falls.

In response to a balance disturbance while standing, either a sway strategy or a stepping strategy is used. A sway strategy is effective when the disturbance is small, but larger disturbances require a stepping strategy. A stepping strategy involves expanding and often moving the base of support by taking one or more steps. [7]. The ability to recover balance using a single step has been shown to associate with both the length and speed of the step [8, 9]. Furthermore, it has been demonstrated both experimentally and theoretically that as disturbance magnitude is increased, a larger step is required [10-12]. A multiple step response, however, can be used to reconfigure the base of support beyond the position of the first stepping foot. Older adults have been shown to take multiple steps more often than young and to transition from a single to multiple step strategy as disturbance magnitude is increased [13, 14]. Furthermore, number of steps taken has been shown to be predictive of future fall risk [15]. While the transition from a sway strategy to a stepping strategy has been studied [6, 16], the conditions for and biomechanical costs of the transition between single and multiple step strategies are not known. Since the transition threshold between balance recovery strategies may be an effective measure of fall risk, the methods used to determine the transition and the biomechanical costs of the transition need to be better understood.

In this study, healthy young participants were asked to recover from a forward fall. Available first step was controlled by instructing the participant not to step over a visible boundary line, which was projected on the floor directly in front of them. Increasing or decreasing the available first step length induced a transition between single and multiple stepping strategies, and recorded responses on either side of the transition threshold. Three aspects of the transition between single and multiple steps were investigated: (1) How does the transition direction (e.g. single-to-multiple versus multiple-to-single) affect the transition threshold? (2) What effect do verbal instructions (e.g. take only a single step) have on the transition threshold? (3) How do the biomechanics of the preparation phase and first step compare on either side of the transition threshold? The following hypotheses were tested: (1) The transition threshold occurs at a shorter available step length when the threshold is approached from the single step side. (2) Verbal instructions to use only a single step cause the threshold to occur at a shorter available step length. (3) The biomechanics of the preparation phase and first step are different on either side of the transition threshold.

2. Methods

2.1 Participants

Fourteen healthy young adults (mean age 23 years, standard deviation 2.7 years, 9 men, 5 women) participated in the study. All participants provided written consent as approved by the University of Kansas Human Subjects Committee - Lawrence Campus. No participant reported cardiovascular or neurological disease or musculoskeletal impairments that affected their ability to exercise.

2.2 Balance disturbance

A balance disturbance was introduced using a sudden release from an initial forward lean [10, 17]. Participants wore a safety harness, attached to a load cell mounted overhead, which allowed multiple steps but would not allow the knees to touch the ground during a fall.

The participant stood with feet shoulder width apart wearing a waist belt attached via a rope to the release mechanism. Initial foot position was marked with tape to maintain consistency across all trials. The participant was instructed to relax ankle muscles while leaning forward with their weight supported by the rope. Foot-floor reactions were monitored in real time, and the cable length was adjusted until the net shear force equaled 18% of the vertical force. Post hoc the mean initial lean angle, based on body configuration and measured between the lateral maleoli to the body’s center of mass, was approximated [10] to be 14.2 degrees with a standard deviation of 1.5 degrees across all participants, suggesting a well controlled initial lean angle.

Once the desired lean angle was achieved, the participant was instructed that the trial would begin, and after a random delay of up to ten seconds, the rope was released. White audible noise was used to obscure audio cues from the release mechanism.

2.3 Boundary line

Available step length was controlled by projecting a laser line onto the floor directly in front of the participant and oriented parallel to the mediolateral axis. The line position was adjusted using a microcontroller-driven motor that oriented a mirror. The experimenter commanded the microcontroller by interacting with a customized LabVIEW (National Instruments, Austin, TX, USA) interface on a desktop computer. The boundary line was presented at locations on the floor such that when the participant took a step, the available step length was a predetermined percentage of the participant's height. The presentation of the boundary line significantly affected first step length, resulting in shorter first steps when the line was present than during natural stepping.

2.4 Tasks

Three tasks were used, differing only by the instruction provided. Task instructions were:

“Natural response” (NR) task: respond naturally using one or more steps to regain balance;

“Boundary Response” (BR) task: respond naturally using one or more steps and do not cross over the boundary line with the first step; and

“Single step” (SS) task: do not cross over the boundary line and regain balance using a single step.

The tasks were done in the same order for all participants: NR, BR, and then SS, which resulted in the instructions progressing from least to most restrictive and minimized the chance that a response would be self limited resulting from previous instructions.

For the NR task, five repeated lean and releases were performed. For the BR and SS tasks, the boundary line was incrementally adjusted in order to determine the available step length at which the participant transitioned between single and multiple step strategies. A series of trials in which available step length was incrementally decreased (downward series), followed by a series in which available step length was incrementally increased (upward series), was performed during each task (Figure 1). During the downward series, the initial available step length was 30% body height and incrementally reduced by 2% body height after each trial in which the participant recovered with a single step and successfully complied with the instructions. If the participant took multiple steps, loaded the ceiling harness with more than 10% bodyweight, or stepped over the boundary line with the first step, a second trial was conducted with the same available step length. When the participant failed to recover balance using a single step or did not comply with instructions on two consecutive trials, the downward series ended. The upward series began with an available step length of 8% body height nearer the participant than the final available step length used during the downward series. This 8% drop in available step length between downward and upward series ensured that the downward series began with a short enough available step length at which no participants recovered balance using a single step. After each response in which the participant failed to recover balance using a single step or did not comply with instructions, the available step length was increased by 2% body height. If the participant recovered with a single step and successfully complied with instructions, a second trial was conducted with the same available step length. The upward series ended when balance was recovered using a single step strategy during two consecutive trials, or after the available step length was increased to 30% body height.

2.5 Measurements

Video, motion, force plate, and load cell measurements were recorded for each trial. Foot motion was recorded using an Optotrak 3020 system (Northern Digital Inc., Waterloo, Ont., Canada) sampled at 100 Hz. Three active infrared markers were placed on lightweight rigid bodies and attached to the top of each shoe. Virtual marker locations were calculated based on probed points for the heel, toe, and lateral and medial maleolus using a rigid body stylus. Three force plates (Advanced Medical

Technology Inc., Watertown, MA, USA) measured ground reaction forces. The force plates were arranged such that the participant initially stood with the right and left foot on separate force plates, and the foot used in the first step landed on the third plate located directly in front of the participant. A custom-made biaxial load cell built into the lean and release mechanism measured cable tension and a uniaxial load cell (Futek, Irvine, CA, USA) on the safety harness attachment point measured harness load. Forces were sampled at 1000 Hz on a personal computer using LabVIEW and a 16-bit analog to digital data acquisition board (National Instruments, Austin, TX, USA).

2.6 Data analysis

Transition thresholds were taken to be the midpoint between the final available step length (at which transition had been made), and the penultimate available step length (at which a transition had not yet been made). In SS trials any change in performance, including taking multiple steps, using the harness for recovery, or stepping over the line, was counted as a transition. However, in the BR set we treated any trials in which the participant stepped over the line or weighted the ceiling harness with more than 10% of their body weight as failures to comply with instructions rather than strategy transitions. Thus, if a participant repeatedly stepped over the line during BR, no threshold could be determined.

Parameters were used to quantify the biomechanics of the first step during natural steps and single or multiple steps taken on either side of the threshold. Natural response parameters were averaged over the last three NR trials. Single and multiple step parameters were calculated from the last successful single step response above the threshold and the first successful multiple step response below the threshold, respectively, during the downward series of BR. Thus, we compared trials in which single versus multiple steps were taken while holding instructions constant and varying available step length by only small amount. Since the biomechanical effects of limiting step length have been studied [9, 10], we did not consider comparisons between natural responses and restricted step lengths.

Analog and motion data from all trials was processed using Matlab (Mathworks, Natick, MA, USA). Force plate and load cell data were digitally low pass filtered using a Butterworth filter (2nd order, 30 Hz cutoff). Forward and backward passes were used to minimize phase shift.

Disturbance onset was defined as the time when the rope force dropped below 8% of the participant's bodyweight. Foot liftoff and landing times were defined as when the vertical ground reaction force dropped below or rose above 10 Newtons, respectively. Step length in the anterior and medial directions were defined as the difference between the step foot toe's initial position and mean position during the window of 100 to 200 ms after contact. Positive medial step length corresponded to movement of the stepping foot towards the stance limb. Available step length was defined as the distance from the toe initial position to the boundary line. Step length boundary margin was defined as the difference between step length and the available step length, which was positive when the step foot landed short of the boundary line.

Force rise time was defined as the time when the vertical ground reaction force under the stepping foot began to rise following disturbance onset. Center of pressure (COP) was calculated from foot-floor reactions. Anticipatory postural adjustment (APA) magnitude was the distance that the center of pressure moved toward the stepping foot prior to liftoff. Foot landing phase was characterized by the peak force magnitude (F_{max}), calculated from the vector sum of forces under the landing foot, and whole body braking force ($F_{braking}$) computed from the time average of the summation of all ground reaction forces in the anteroposterior direction during the 100ms following foot contact.

The number of steps taken and whether or not the first step crossed the line were identified visually during the testing session in order to guide the protocol and checked post hoc using the foot movement data to verify accuracy. In the post hoc analysis, a second step was defined if either toe advanced more than 5mm past the first step length. In three instances, post hoc analysis indicated that one set of trials should have been terminated due to a change in strategy, while visual analysis did not detect the change. In this case, we analyzed the data set as if the post hoc analysis had been available to guide the testing—that is, trials occurring after the set that should have been terminated were not included in the analysis.

Previous studies have shown no gender-related differences in young participants' maximum recovery ability or normalized step length [11, 18], but significant differences in peak joint torques [19, 20]. However, since we made intrasubject comparisons across conditions, rather than across participants, we pooled all participants into a single group.

2.7 Statistics

Microsoft Excel 2000 (Microsoft, Redmond WA, USA) was used for statistical analysis. Effect of instruction set, direction of testing (upward and downward series), and number of steps was evaluated using intrasubject paired t-tests with a significance level of $p<0.05$.

3. Results

3.1 Success rates and existence of threshold

The transition threshold during TR was quantified in 50% of participants (6 men and 1 woman). Reasons for exclusion included weighting the harness with more than 10% body weight, stepping over the line, or exhibiting only multiple step strategies. During SS, transitions were quantified in 93% and 86% of participants during downward and upward series, respectively. Table 1 summarizes the number of participants included in each comparison, and figure 2 summarizes the reasons for each exclusion.

3.2 Effects of transition direction and instruction

Instruction set did not have a statistically significant affect on threshold during the downward series (Table 2, Figure 3). However, the order of boundary presentation (downward versus upward series) significantly affected the threshold in the boundary response condition (p<.05): the threshold occurred at longer available step lengths in the upward, compared to the downward, series. The order of boundary presentation did not affect the threshold when single steps were instructed.

3.3 Biomechanics of first step

Timing:

The first step of a multiple step response, compared to the single step, lifted off significantly later (p<.05) (average delay 11ms) with a significantly shorter swing time (p<.001) (average 32 ms shorter) (Table 2, Figure 4). No differences in the push-off time between single and multiple step responses were observed.

Kinematic Characteristics:

The first step of a multiple step response, compared to a single step, was significantly shorter (p<.001) (average 5% body height shorter) and landed significantly further behind the line (p<.01) (average 3% body height further) (Table 2, Figure 5). Though not reaching statistical significance, a trend was observed that the medial step length was 1.3% body height less for the multiple step compared to the single step response. No step strategy differences were observed in step velocity.

Kinetics:

Prior to foot lift off, APA magnitude was not significantly different between single and multiple step responses. $F_{braking}$ was significantly lower ($p<.001$) when a multiple, compared to single, step was taken (average 7.8% body weight lower) However, no strategy differences were observed in F_{max} (Table 2, Figure 6).

4. Discussion

4.1 Effect of direction

We tested the hypotheses that the transition threshold between single and multiple step responses to a balance disturbance depend both on transition direction and instruction. We found that when no constraints are placed on the number of steps taken, transition threshold is affected by the direction from which it is approached. The transition displayed hysteresis such that strategy utilized in the current trial was more likely to match that strategy used in the previous trial. Of the six participants for whom effect of direction was quantified, four exhibited a hysteresis effect, with the others exhibiting the same transition threshold in both directions. Hysteresis has been shown in other motor tasks including the transition between reaching with forearm pronation versus supination [21] and walking versus running [22]. While a protocol change including a random presentation of available step length, instead of an incremental step length change as used in the current study, might minimize the hysteresis, pilot data indicated that it also decreased the participant's ability to successfully perform the task. It is also possible that by defining the threshold as occurring only when two consecutive trials exhibit a changed strategy, the protocol was biased towards overestimated hysteresis. More sophisticated protocols, such as the adaptive staircase method, may provide an alternative method to determining the threshold [23]. If transition threshold is shown to be of clinical significance, then the method used to quantify the threshold should be further investigated.

4.2 Effect of instruction

We did not observe instructions limiting the number of steps to affect the magnitude of the transition threshold. This suggests that the transition threshold during the boundary response task was near the minimum step length at which participants could recover with a single step. However, the inability of this protocol to detect transition thresholds greater than 30% body height may have introduced a bias. Three participants took multiple steps at an available step length of 30% body height, but took single steps during the NR and SS. Therefore, they may have a transition threshold that lies between 30% body height and their natural step length, resulting in these participants being excluded from analysis. Therefore, the effect of instruction may have been obscured by exclusion of participants for whom instruction had the largest impact.

4.3 Biomechanics of first step

We examined how the transition between single and multiple step strategies during recovery from a forward fall affects the biomechanics of the preparation and execution of the first step. We found that differences between single and multiple step responses can be detected as early as liftoff of the first step foot. Although liftoff time changed on average by only 11 ms, or 5%, between single and multiple step responses, intrasubject paired comparisons demonstrated the statistical significance of the change. This finding suggests that the step preparation phase may not be as invariant as originally proposed by Do et al. [24] and supported by King et al. [17], but instead may correspond to the planned step strategy. In a follow-up to their original balance recovery study, Do et al. [25] found that step liftoff time decreased by 30ms when the challenge of the balance recovery task was increased either by biomechanical or instructional constraint. They interpreted this as indicating that liftoff time is decreased according to the participant’s assessment of the risk of fall. If this reasoning is applied to our study, we might conclude that participants interpreted a multiple step strategy as less risky, and thus they delayed the step liftoff. Regardless of the reason for the link between step strategy and liftoff time, the existence of this relationship provides support for the argument that stepping strategy is determined prior to liftoff of the first step, rather than only after the first step has failed to successfully recover balance.

The biomechanics of the single and multiple step strategy diverge more profoundly after the step liftoff time. A much shorter swing time, coupled with a reduced step length that lands further behind the boundary line, is seen when multiple steps are taken. Furthermore, the 100 ms following landing of the first step are characterized by an 84% reduction in whole body average braking force. Taken together, these characteristics suggest that when multiple steps are taken, the first step serves to quickly reconfigure the base of support to provide a supporting rather than braking force, while a second step is prepared which will generate sufficient braking forces to arrest the participant's forward momentum.

These findings compliment the findings of Cyr et al, who in separate studies found the kinetics[19] and kinematics[18] of the first step to be affected by the number of steps taken. They found that participants took on average 9 cm shorter first steps when allowed to respond with multiple steps compared with when instructed to respond with a single step. In the present study, first steps in multiple step responses were an average of 5% body height, or 8.6 cm, shorter than during single step responses. Although the Cyr study did not perform statistics on liftoff time, the mean liftoff times can be computed from the sum of reaction time and weight transfer times. Using this method, their mean liftoff time is approximately 5ms shorter for multiple steps compared to single steps. However, we found that mean liftoff time was 11ms *longer* for multiple steps. This difference could be caused by the fact that Cyr et al. tested participants at their maximum lean angle, resulting in an increased perceived fall risk and therefore decreased liftoff time during both single and multiple stepping, as predicted by Do et al [25].

The force rise time computed in this study corresponds in definition to reaction time or push-off time in other studies [10, 26]. Interestingly, we found average force rise times much lower than others. For example, the fastest group reaction times reported by Thelen et al. [10] and King et al. [17] were 57 and 68 milliseconds, respectively. The average force rise time during natural response in this study was 39 milliseconds. While others have attributed the rise in vertical ground reaction force following the lean and release to reflexes [25], the discrepancy between the results of this study and others suggest that factors other than fixed-latency reflexes are involved. Initial data taken to investigate this phenomenon points to decreased gastroc activation prior to disturbance leading to shorter force rise times. It is possible that our focus on coaching participants to relax their ankle muscles contributed to the short force rise times that we observed.

4.4 Protocol uniqueness

A unique aspect of this study is that we manipulated the task challenge by adjusting the available first step length while initial lean angle remained constant at an amplitude well within participants' balance recovery ability. Others have manipulated task challenge by changing the lean angle only [10, 11], instructions at a maximum lean angle [19], or step length at maximum lean angle [9]. While testing at the maximum lean angle allows recovery ability to be directly compared across participants, testing at smaller lean angles may be less intimidating and safer, especially for older adults and adults with movement disorders (e.g. Parkinsons disease).

4.5 Existence of threshold

In this study several participants from some of the analysis. Of 14 original participants, only 7 successfully transitioned from single to multiple steps during the downward series of BR, and only 6 of the remaining transition to single steps during the upward series. The exclusion rate was higher among women (80%) than men (33%), suggesting that gender affected our ability to detect the transition threshold. Since we could only detect transition thresholds at available step lengths of less than 30% body height, a possible explanation for the high exclusion rate among women is that they have a longer transition threshold than men. However, we did not have a large enough participant pool to perform statistical analysis on the effects of gender. The participants excluded reported engaging in slightly less weekly exercise (average 2.4 compared to 3.7 hours per week), although the difference was not statistically significant. Future experiments should include trials at longer available step lengths, and include appropriate numbers of men and women to quantify gender effects.

4.6 Future study

In this study, only healthy young participants were considered. However, our finding that the first step is shorter during multiple stepping is consistent with Luchies et al. [13] who demonstrated that older adults take a shorter first step and more frequent multiple steps. Future study should address the strategy transition in older adults and investigate possible correlations between transition threshold and fall risk.

4.6 Conclusion

In conclusion, we have shown that a transition between single and multiple step strategies can be induced by restricting available first step length, and that the magnitude of the transition threshold is affected by the direction from which the threshold is approached. Therefore, if transition threshold is used as a clinical or experimental measure of balance performance, then the method used to determine the threshold is important. We have also shown that the biomechanics of the first step are different on either side of the threshold. This suggests that the planned step strategy is determined early in the response, rather than only after the first step fails to recover balance. Therefore, caution should be used when comparing biomechanics between single and multiple step responses.

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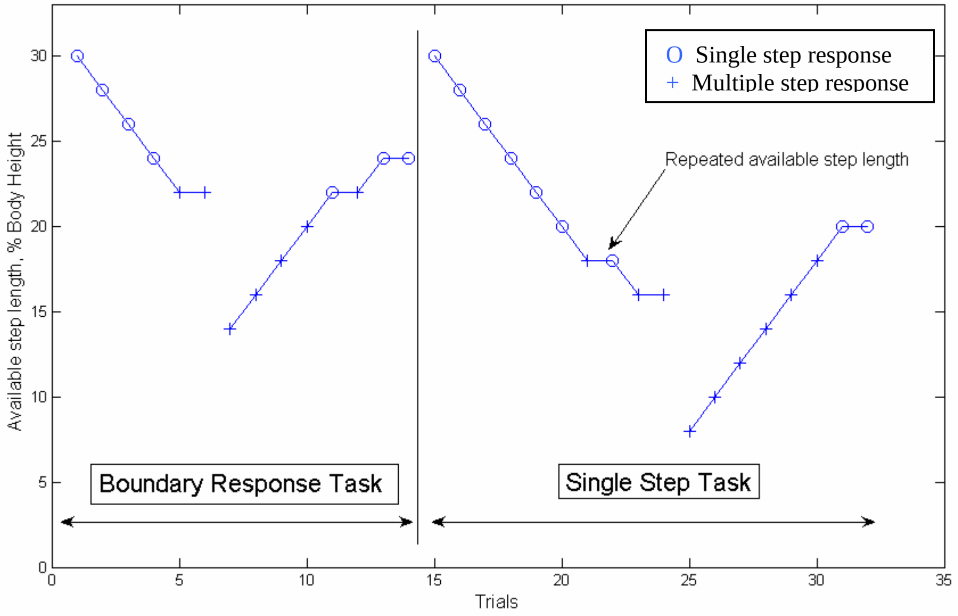


Figure 1. Available step lengths during downward and upward series of BR and SS. When stepping strategy changes, the available step length is repeated in the next trial. When the new strategy is used in two consecutive trials, the series ends.

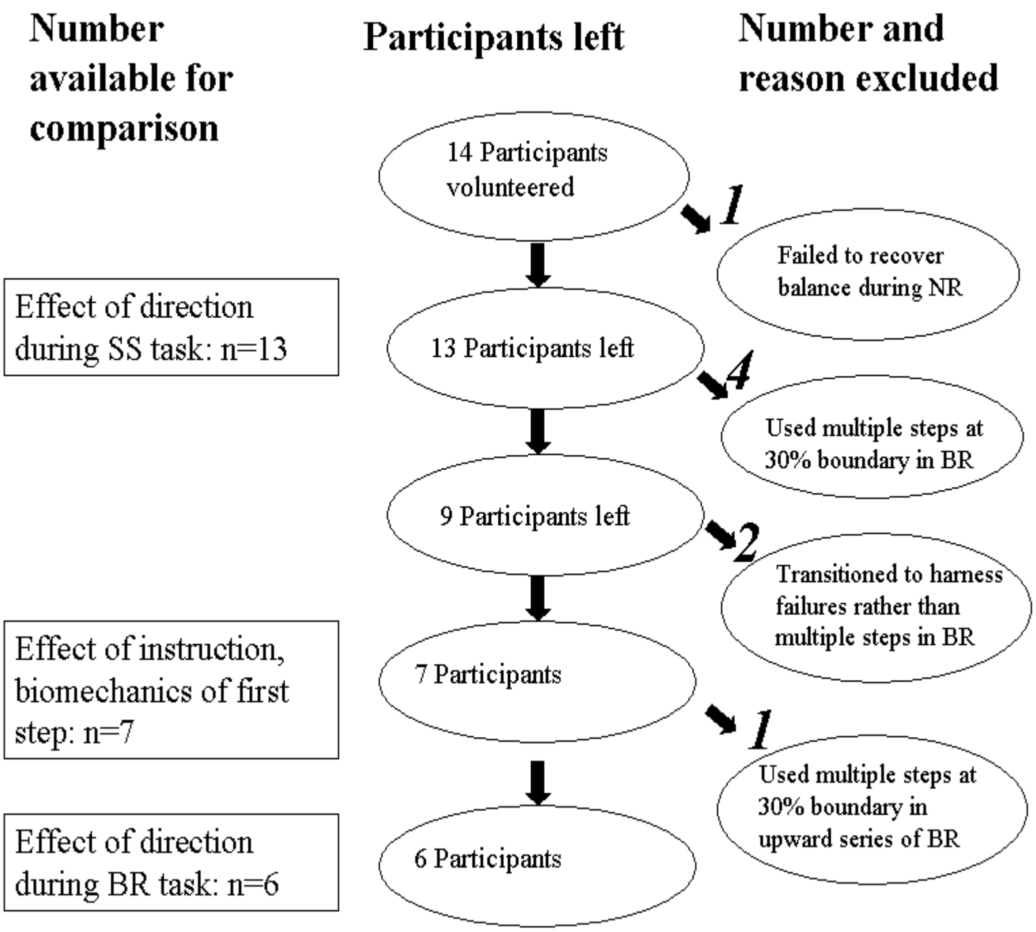


Figure 2. Exclusion criteria (right column) that determined the number of participants who could be included for each comparison (left column). Failure to recover balance during natural response, use of multiple steps at longest available step length during (BR) task, harness failures, or use of all multiple steps during only the upward series of BR resulted in exclusion from some analyses.

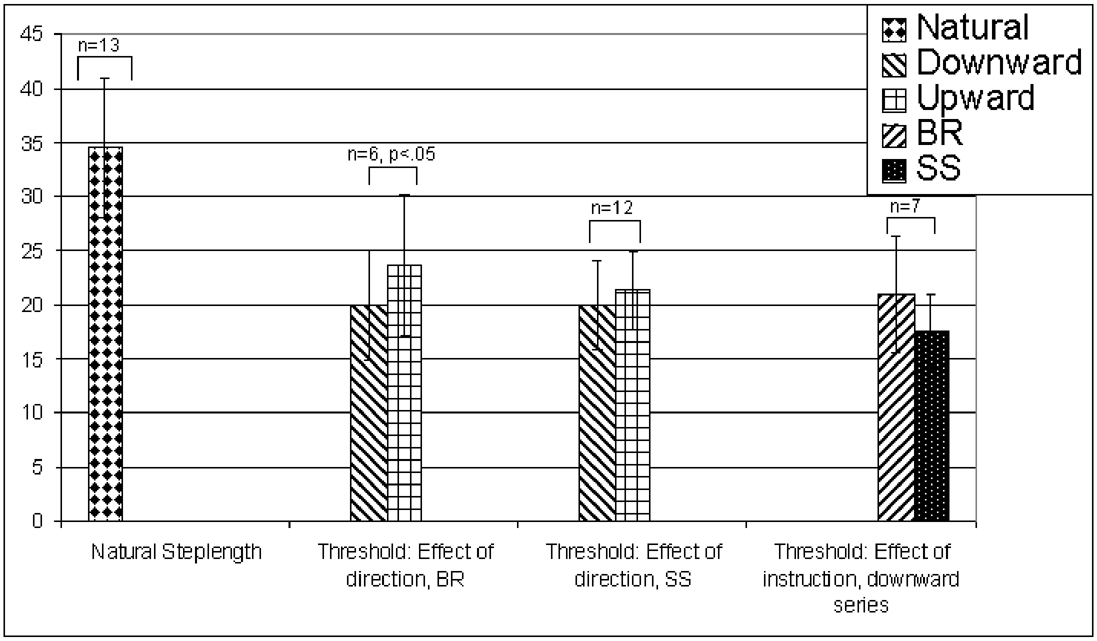


Figure 3: Mean natural anterior step length and transition threshold during BR and SS tasks. Each bar represents the mean transition threshold among only those participants who were included in the applicable comparison.

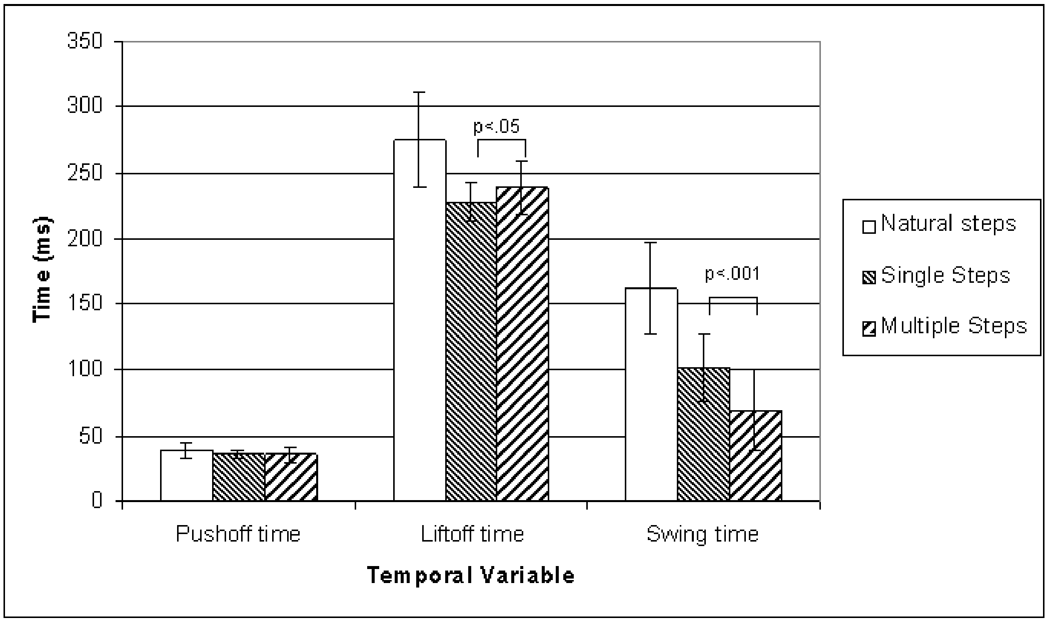


Figure 4: Mean values of temporal variables during natural steps and single or multiple steps taken on either side of the threshold. N=7 for all parameters.

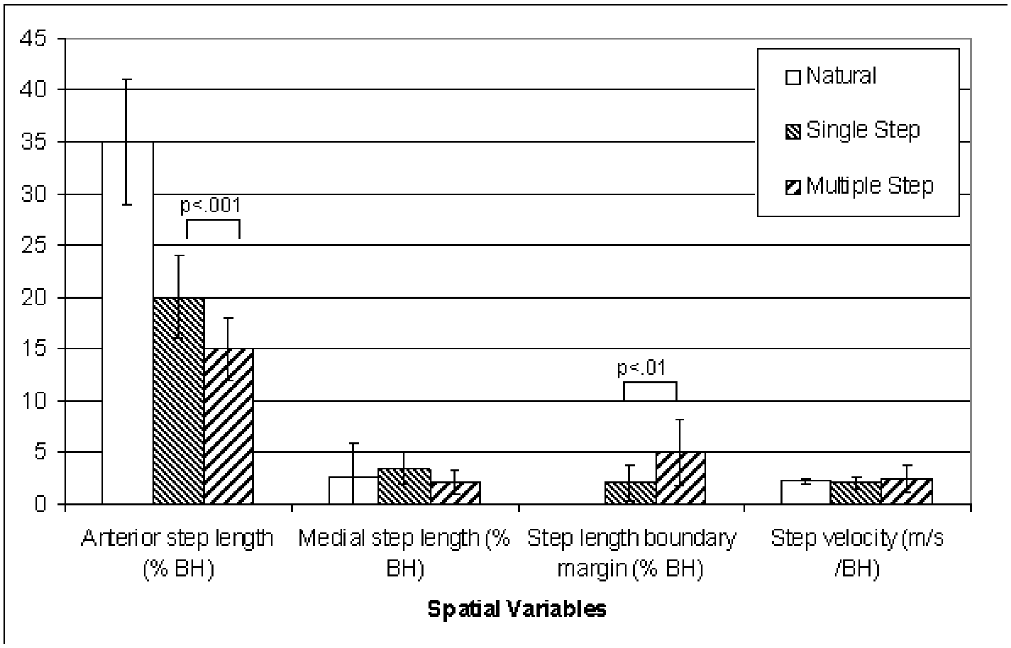


Figure 5: Mean values of kinematic variables during natural steps and single or multiple steps taken on either side of the threshold, scaled to body height. N=7 for all parameters.

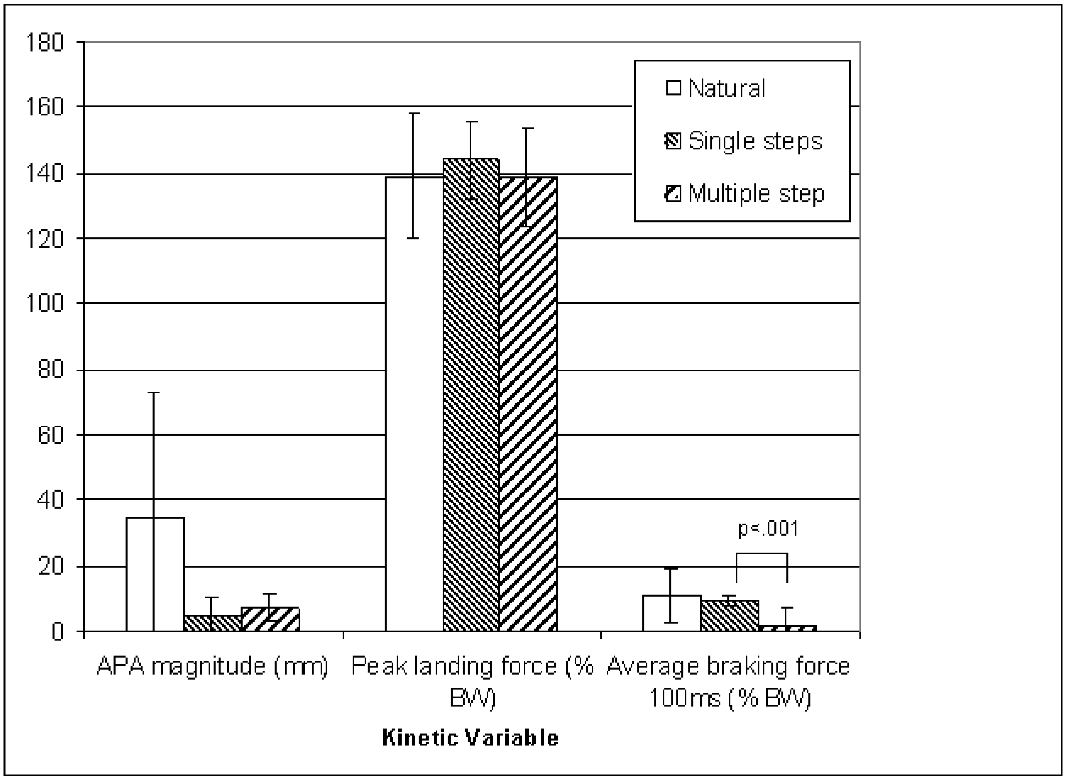


Figure 6: Kinetic variables during natural steps and single or multiple steps taken on either side of the threshold. N=7 for all variables.

Table 1: Number of participants who exhibited strategy transitions in each task and were included in each comparison.

	Number of participants
Observed strategy transitions:	
Boundary Response task: down	7
Boundary Response task: up	7
Single Step task: down	13
Single Step task: up	12
Made comparisons:	
BR: Effect of direction	6
SS: Effect of direction	12
BR vs. SS: Effect of instruction	7
First step biomechanics: Effect of strategy	7

Table 2: Mean parameter values during NR (Considering all participants), and during multiple and single step responses on either side of the transition threshold (Considering only participants for whom comparisons were made). P values from intrasubject paired t-tests are also given. * p<.05, n=7.

	Natural	Multiple step	Single step	Paired test p value multiple vs single
Force rise time (ms)	39 ± 5	36 ± 6	36 ± 3	0.593
Liftoff time (ms)*	275 ± 36	239 ± 20	228 ± 15	*<.05
Swing time (ms)*	162 ± 35	70 ± 31	102 ± 25	*<.001
Step length (% bh)*	35 ± 6	15 ± 3	20 ± 4	*<.001
Medial step length (%bh)	2.7 ± 3.1	2.1 ± 1.1	3.4 ± 1.5	0.064
Boundary margin (% bh)*	---	5 ± 3.2	2 ± 1.7	*<.01
Step velocity (m/s /bh)	2.2 ± .3	2.5 ± 1.3	2.1 ± .6	0.241
APA magnitude (mm)	35 ± 38	7 ± 4	5 ± 5	0.29
F_{max} (%bw)	139 ± 19	139 ± 15	144 ± 12	0.273
$F_{braking}$ (%bw)*	10.9 ± 8.2	1.5 ± 5.2	9.3 ± 1.6	*<.001

CHAPTER FOUR: SUMMARY

Summary of study

Falls are a significant health concern, especially amongst older adults. Better understanding of the mechanisms of balance recovery is crucial to developing diagnostic techniques and interventions to prevent falls. Since older, compared to younger, adults have been shown to more often take multiple shorter steps in response to a balance perturbation, and since taking multiple steps has been shown to correlate with increased fall risk, the transition between single and multiple step strategies is of particular interest.

The goal of this study was to investigate the conditions for and biomechanical costs of the transition between single and multiple step strategies during recovery from a forward fall. Healthy young participants were released from an initial forward leaning position, and a transition between single and multiple step strategies was induced by limiting the available first step length. This method allowed the identification of the available step length threshold at which the participant transitioned from a single to multiple step strategy. Three research questions were addressed:

> (1) How does the transition direction (e.g. single-to-multiple versus multiple-to-single) affect the transition threshold?

(2) What effect do verbal instructions (e.g. take only a single step) have on the transition threshold?

(3) How do the biomechanics of the preparation phase and first step compare on either side of the transition threshold?

Video, motion, and force data were recorded. Biomechanics of the first step were characterized based on timing, kinematic, and kinetic parameters. Paired comparisons were used to evaluate how the first step performance varied with stepping strategy (single versus multiple steps).

Transition direction caused significant hysteresis in the magnitude of the transition point. While statistically significant instruction effects were not found, there is reason to believe that other protocols could detect changes in boundary threshold as the number of steps is limited.

For steps near the transition threshold, the first step in the balance response lifted off significantly sooner and landed closer to the boundary line when a single step, rather than a multiple step response, was used. The landing phase was also characterized by higher braking forces when a single step was used. These results suggest that step strategy may be chosen before liftoff of the first step, and that the first step is modified in preparation for subsequent steps to be taken.

Conclusions & recommendations

The results of this study indicate that step strategy affects the first step utilized in response to a forward loss of balance. Therefore, in future studies it may not be appropriate to pool single and multiple step responses for statistical analysis. However, since participants may naturally prefer to respond to a disturbance using multiple steps, and we have shown that changing stepping strategy alters biomechanics of the first step, limiting the number of steps with instructions is likely to lead to results that are not indicative of natural performance. This may be especially true when comparing groups of older participants, since they have been shown to commonly use multiple steps to recover balance. The most rigorous approaches to quantifying balance response will determine the naturally chosen recovery strategy, and carefully consider how instructions affect performance.

Study limitations

A primary limitation of this study was the need to disqualify over 50% of participants from parts of the analysis due to participant behavior that made comparisons impossible. Four participants took only multiple steps when the number of steps was not limited, so no transition was observed. While these participants may have taken single steps given a sufficiently large available first step length, the physical size of the force plates and the floor setup did not accommodate larger steps for all participants, and the protocol made no provision for testing boundary locations greater than 30% body height. A redesigned protocol that incorporated some testing at longer available step lengths, and a hardware setup that accommodated this protocol, may have resulted in the inclusion of additional participants in the data analysis.

The multiple failure modes in the single step task presented a further challenge. Failures could occur when the participant used the ceiling harness for support, took multiple steps, or stepped over the line. The variety of causes for failure meant that these responses could not be grouped together for analysis, and biomechanics on the multiple step side of the threshold were not considered.

Participant compliance and motivation are difficult to assess in this type of a study. Since participants were tested at available step lengths near the limits of their ability, they inevitably violated the instructions at some point during the test. Whether the instructions were violated because the performance goals could not be reached or from lack of motivation cannot be known. Future studies could incorporate alternative methods for limiting first step length—for example, a physical obstacle could be placed at the step length boundary so that participants cannot violate the instructions and step beyond the boundary.

Further study

In this study, available step length was incrementally reduced or enlarged and hysteresis was observed based on the direction of the available step length change. If the transition threshold is shown to be of clinical significance, methods to accurately estimate the threshold without hysteresis should be studied. For example, the effect on the threshold of varying available step length randomly, rather than incrementally, could be investigated.

Since older adults are especially likely to take multiple steps in response to a balance disturbance, and the number of steps taken has been shown to correlate with fall risk, the single to multiple step transition threshold should be studied in the older population. Understanding the correlation between step strategy and fall risk might lead to improved fall risk assessments and inform whether interventions aimed at modifying step strategy are appropriate.

This study addressed only induced forward falls. Further study should address the step strategy transition in the lateral and backward directions. Since a visible boundary line may not be effective at controlling first step length during lateral or backwards perturbations, other methods of inducing the transition could be tried, including varying disturbance magnitude.

Patients with Parkinson’s disease have been shown to be less consistent in their choice of stepping foot than healthy participants. Since this study investigated only one aspect of stepping strategy (number of steps), future studies could investigate the effects of stepping with dominant versus non-dominant foot.

APPENDIX CONTENTS

SUBJECT CONSENT FORM

Approved by the Human Subjects Committee Lawrence Campus, University of Kansas. Approval expires one year from 9/12/2008. HSCL #17535

FUNCTIONAL ASSESSMENT OF MOTOR CONTROL

INTRODUCTION

The Department of Mechanical Engineering at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and not participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY

The purpose of this study is to provide a better understanding of physical function in healthy adults. This will be accomplished by collecting movement, force, muscle activity, and balance data during functional activities.

PROCEDURES

As described in the following PROTOCOL CHECKLIST, you are being asked to participate in one or more components of this study. There are five potential components: (1) evaluation of clinical and cognitive status, (2) evaluation of movement, (3) evaluation of force, (4) evaluation of muscle activity (EMG), and (5) evaluation of balance. Often, (2), (3), and (4) are conducted together. For instance, while we have you walk, we may look at the movement of your joints, collect data about the force you are exerting on the floor, and look at your muscle activity all at the same time.

The specific components that you are being asked to participate in will be described to you by the research staff member and are marked on the PROTOCOL CHECKLIST. These components have been chosen by Dr. Luchies based on the particular scientific question in hand and the current stage of research study development. We ask that you initial the tasks you agree to do.

As a participant, you will be asked to complete each selected component no more than one time. The combined time on all activities will not exceed 5 hours in one day and will not exceed two consecutive days of testing.

You participation in these tasks may be videotaped. These tapes will be used by the researchers only and stored in a locked cabinet.

PROTOCOL CHECKLIST: Biodynamics Laboratory Testing Protocols

Balance Task	**Subject Initials**	**Measurement**	**Subject Initials**
1a. Forward Lean	________	2a. Clinical and Cognitive Testing	_________
1b. Backwards Pull	________	2b. Force Testing: Lower Body	_________
1c. Treadmill Gait	________	2c. Force Testing: Strength	_________
1d. Over ground Gait	________	2d. EMG	_________
1e. Postural Sway	________	2e. Movement Testing	_________
1f. General Movement Tasks	________		

The total estimated time for completion of all components of this project is: _______________.

The study will be divided across __________ test sessions.

DETAILED STUDY METHODS AND PROCEDURES

1a. Forward Lean: For this test, we will be looking at your response to a balance disturbance. You will wear a belt around your waist and a safety harness that attaches over your shoulders, across your chest, and around your legs as well as to our ceiling to protect you from a fall. We will ask you to stand in a forward leaning posture, while supported by a counter weight. When the weight is released, you will take action to restore your balance, which may include taking a forward step. During the testing, you may be asked to target a line on the floor with your step or to perform a distraction task, such as counting or squeezing a ball. You will be able to take a seated rest as needed between trials.

1b. Backwards Pull: For this test, we will be looking at your response to a balance disturbance. You will wear a belt around your waist and a safety harness that attaches over your shoulders, across your chest, and around your legs as well as to our ceiling to protect you from a fall. You will start by standing relaxed. After a short period, you will feel a tug at your waist. You will be asked to respond naturally to the tug and may need to take a step to keep your balance. During the testing, you may be asked to perform a distraction task, such as counting or squeezing a ball. You will be able to take a seated rest as needed between trials.

1c. Treadmill Gait: For this task, we will be looking at your gait kinematics. You will wear a safety harness that attaches over your shoulders, across your chest, and around your legs as well as to our ceiling to protect you from a fall. You will start by standing relaxed on a treadmill. We will slowly increase the speed of the treadmill until we reach your comfortable walking speed. You will then continue walking for up to ten minutes.

1d. Over ground Gait: For this task, we will be looking at your ability to start walking. You will wear a safety harness that attaches over your shoulders, across your chest, and around your legs as well as to our ceiling to protect you from a fall. You will start by standing relaxed. A visual cue (light) will be given to you to start walking. You will then take up to five steps.

1e. Postural Sway: For this test, we will look at your standing balance. You will wear a safety harness that attaches over your shoulders, across your chest, and around your legs as well as to our ceiling to protect you from a fall. You will stand relaxed while we record the natural sway of your body. You may be asked to stand with your eyes open or closed. You will be able to take a seated rest as needed between trials.

1f. General Movement Tasks: For these tasks, we will look at look at your performance of general movement that are similar to normal activities of daily living. These may include rising from a sitting to a standing position, sitting and reaching, or grasping and moving small objects. You will wear a safety harness that attaches over your shoulders, across your chest, and around your legs as well as to our ceiling to protect you from a fall.

2a. Clinical and Cognitive Testing: For these tests, we will be collecting information about you that will help us evaluate your physical functioning. For instance, we need to know your general abilities with respect to language, memory, and current physical status. We will test your memory and thinking. We will also look at your physical abilities with questionnaires or with physical testing such as sensation, movement, or range of motion measurements. Also, we will look at your endurance and your strength. Combined, these tests typically take between 15-30 minutes to complete.

2b. Force Testing: Lower Body: We will be looking at the forces your legs produce while doing an activity such as walking or standing. This testing will be done at the same time as the marker tracking or balance testing and will not require additional time.

2c. Force Testing: Strength: Your strength and/or muscle tone will be tested with a measurement device. You may be asked to move with the device, move against the device, relax while the device moves you or give a maximal contraction while the device collects data. These tests typically take between 30-60 minutes with rest as needed.

2d. Assessment of Muscle Activity/EMG: Our EMG system measures your muscle activity. Surface electrodes are applied to your skin over your muscle. Alcohol wipes are used to clean your skin and then two electrodes are placed over each area. Most often your lower leg and thigh muscles are monitored including anterior tibialis, gastrocnemius, quadriceps, and hamstrings. But, we may want to monitor your hand and arm muscles if you are doing an upper body task. Our EMG system gathers information from your muscles but does not give any feedback back to you. Application of the electrodes takes approximately 10-15 minutes.

2e. Movement Testing: For these tests, we will place markers on your skin to monitor your movements while you perform an activity. Possible activities may include one or more of the following: walking on level surfaces or stairs, walking on a treadmill, rising from a chair, or reaching for or lifting an object. Application of the markers and setup for movement testing takes approximately 20 minutes.

RISKS

Understand that there may be possible risks for participating in this study:

- Clinical/Cognitive: there may be a risk of falling during balance portions of the clinical testing, but the risk will be minimized by close monitoring by a research assistant. There is also a small risk of fatigue with the cognitive testing, but we will allow you to take breaks if necessary.
- Movement Testing: There are no known risks to marker or device tracking. There may be a risk of slight muscular fatigue from the performance of multiple repetitions of certain activities, but this should resolve in 24-48 hours.
- Force Testing: There may be some muscular soreness from the strength testing, but this should resolve in 24-48 hours.
- EMG: There are no known risks to the use of EMGs. There may be some skin irritation under the electrodes.
- Balance Testing Tasks: There may be a risk of falling during the balance testing but this risk will be minimized by the use of a safety harness and the close monitoring by the research associate.

BENEFITS

There are no direct benefits to you for participating in this study. It is hoped that information will be gathered about healthy adults to help with ideas for and comparison with research studies with adults with disease.

PAYMENT TO PARTICIPANTS

There is no payment for participating in this study.

PARTICIPANT CONFIDENTIALITY

To perform this study, researchers will collect information about you. This information will be obtained from a questionnaire that will assess if you have health or heart problems that might make too much walking or the activity previously described inadvisable. Also, information will be collected from the study activities that are listed in the Procedures section of this consent form. This includes information about your age, height, and your weight.

Your name will not be associated in any way with the information collected about you or with the research findings from this study. The researcher(s) will use a study number instead of your name.

Some persons or groups that receive your information may not be required to comply with the Health Insurance Portability and Accountability Act's privacy regulations, and your information may lose this federal protection if those persons or groups disclose it.

The researchers will not share information about you with anyone not specified above unless required by law or unless you give written permission.

Permission granted on this date to use and disclose your information remains in effect indefinitely. By signing this form you give permission for the use and disclosure of your information for purposes of this study at any time in the future

INSTITUTIONAL DISCLAIMER STATEMENT

In the event of injury, the Kansas Tort Claims Act provides for compensation if it can be demonstrated that the injury was caused by the negligent or wrongful act or omission of a state employee acting within the scope of his/her employment.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION

You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION

You may withdraw your consent to participate in this study at any time. You also have the right to cancel your permission to use and disclose information collected about you, in writing, at any time, by sending your written request to: Carl W. Luchies, Ph.D., Mechanical Engineering Department, 1530 W. 15th Street, Lawrence, KS 66045. If you cancel permission to use your information, the researchers will stop collecting additional information about you. However, the research team may use and disclose information that was gathered before they received your cancellation, as described above.

QUESTIONS ABOUT PARTICIPATION should be directed to Carl W. Luchies, Ph.D.,
Principal Investigator, Mechanical Engineering Dept., 3181 Learned Hall, University of Kansas
Lawrence, KS 66045, 785 864-2993

If you have any questions about your rights as a research participant you may contact the Human Subjects Committee Lawrence Campus (HSCL) office at 864-7429 or 864-7385 or write the Human Subjects Committee Lawrence Campus (HSCL), University of Kansas, 2385 Irving Hill Road, Lawrence, Kansas 66045-7563, email dhann@ku.edu or mdenning@ku.edu.

KEEP THIS SECTION FOR YOUR RECORDS. IF YOU WISH TO PARTICIPATE TEAR OFF THE FOLLOWING SECTION AND RETURN IT TO THE RESEARCHER(S).

____

(Project/Study Title)

HSCL #___17535________________ (Provided by HSCL office)

PARTICIPANT CERTIFICATION:

If you agree to participate in this study please sign where indicated, then tear off this section and return it to the investigator(s). Keep the consent information for your records.

I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study and the use and disclosure of information about me for the study.

I agree to take part in this study as a research participant. By my signature I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form. *(Use the 18 years old disclaimer only if the study population may include participants under the age of 18).*

________________________________ ______________________
Type/Print Participant's Name Date

____
Participant's Signature or Parent/Guardian Signature if Participant is less than 18 years old or an adult under care of a guardian

[If signed by a personal representative, a description of such representative's authority to act for the individual must also be provided, e.g. parent/guardian.]

Biodynamics Lab Health Screen

*For use with subjects aged 18 to 30 years old

Subject name: ____
Date of screening: ___________
Date of test: ___________
Gender: ___________
Age: ___________
Height: ___________
Weight: ___________

Are you currently participating in any other research studies? _________
If yes, explain:

Do you have any injury or illness that limits your activity level? _________
If yes, explain:

Have you eaten regularly over the past 24 hours? __________

Do you have any history of cardiovascular disease? __________
If yes, explain:

Are you currently taking any medications? __________
If yes, what?

Have you ever had any of the following?

- Heart attack Y
  N

  -
- Heart disease or problems Y
  N

  -
- Chest pain Y
  N

  -
- Seizure Y
  N

  -
- Cancer, leukemia, or lymphoma Y
  N

  -
- Diabetes Y
  N

  -
- Ankle sprains Y
  N

  -
- Dizziness or lightheadedness (including during exercise) Y
  N

  -
- Fainting Y
  N

  -
- Broken bone Y
  N

  -

- High blood pressure Y
  N

- Inner ear damage Y
  N

- Pain or stiffness in hips, knee, or ankle Y
  N

- Back pain Y
  N

- Shortness of breath (including during exercise) Y
  N

- Joint surgery (such as joint replacements or tendon/ligament repair) Y
  N

- Are you currently taking any medications? Y
  N

- Major or minor surgery? Y
  N

- Neurological disease (multiple sclerosis, ALS, Parkinson’s disease)? Y
  N

ACTIVITY:

Are you able to leave house / apartment on your own? How often?

____

When you walk, do you walk with: Self walker/cane person assist unable
How far do you walk on a daily basis? ________
How often do you walk? _______
How long do you walk (duration) _______

Do you participate in any exercise/Activities?
Type ____
Sessions per week ______________________________________
Minutes / hours per session ________________________________

Hand dominance L R Leg dominance L R
(Are you right or left-handed?) (Which leg would you kick a ball with?)

FOR SCREENER USE ONLY:

Subject Identification Number: _________
Date of screening: _________
Date of testing : _________

Subject Name: __________________________

Age: ______
Gender: ______

PASS? YES NO

If no, why not?

If subject answered yes to any questions but was not excluded, please explain reasons:

Comments:

PARTICIPANT RECRUITING POSTER

VOLUNTEERS NEEDED!!!

Do you want to help advance research at KU?

Want to get a first hand look at cutting-edge biomechanics research?

We’re looking for volunteers to participate in a study of human movement.
If you are interested in volunteering, contact
Michael Haines (email mchaines@ku.edu)
or stop by the Biodynamics Research Laboratory (2110 Learned Hall)

IN-DEPT TESTING PROTOCOL

**FILE FOLDERS:*

ALL FILENAMES REFERENCED BELOW IMPLY THE ROOT DIRECTORY
"C:\Documents and Settings\Biodynamics Lab\My Documents\mch\leanandrelease_study\"

Lab Setup:

1. Turn on forceplates, allow to warm up.
    - This will also turn on and warm up the ceiling harness loadcell
    - zero forceplates
2. Plug in lean/release load cell
3. Start "control.vi" to control target positioning system
3. Turn on laser target system (flip power supply switch "on").
    - Move to near home position (click "home")
    - Put the motor on a warmup loop (click "warm up coils")
4. Set up video camera with a fresh tape (have backup take ready as well).
    - Position it so you can clearly see forceplates
    - Have whiteboard ready and in a position to be seen by camera
5. Turn on Optotrak
6. Get subject data folders ready on both computers ("…\data\sid____")
7. Turn on speakers. Make sure white noise generated by the data collection program is proper volume.

Subject setup:

Initial setup:

1. Consent

• Subject needs to consent to 1a, 2b, and 2e on PROTOCOL CHECKLIST

2. Health Screen

- If answered yes to any questions, confirm whether there is a medical problem that presents a risk if tested, or if any medical issues are present which might affect the balance recovery task (i.e., interfere with balance, movement, etc.)

3. Change in to shorts, lab shoes.

Measurements:

Height: Use ruler in changing room. Shoes ON.
Bodyweight: in lbs, measure using scale
Leg length: Troch to medial malleolus
Ankle width: widest measurement from medial to lateral malleolus

Ankle height: floor to middle of lateral malleolus
Foot length, width: largest measurement of length and width

Equipment setup:

1. Put on safety harness (do not connect ropes yet).
2. Add waist belt. Should rest on hip bones. Metal buckle in back.
    - Measure height from floor to middle of buckle. Record under “Rope height”

3. Place marker triads on feet.
    - Triad “A” on right foot
    - Triad “C” on left foot
    - For both triads, marker “1” should point up the foot (away from toe). The foam wedges should angle the triads so that the markers face anteriorly.

4. Velcro strober box to waist belt. Secure wires using combination of duct tape and paper skin tape.

Steplengths list

1. Need to generate table for converting from % bodyheight to number of steps on target positioning system
2. Get subject height (should be first thing measured and recorded on datasheet)
3. Use Matlab to open “table_generator.m” under the folder “…leanandrelease_study\target_position_calibrator\
4. Input calibration date to use
   -To find the most recent calibration, open “…\data\” and find the most recently dated folder labeled “calibration”… e.g., “\calibration_09_19_08”. For this example, the calibration date to enter is “09_19_08”.

5. Input subject height in cm
6. A spreadsheet will be created under the subject data folder (\data\sid####) relating % bodyheight to number of steps. Open this spreadsheet & print it.

Static Trials (probing):

1. Set up Optotrak coordinate system
2. Start a new experiment in appropriate sid directory
    - Under “…\data” create a folder named “sid####” with the appropriate subject ID number (e.g., “\sid1001”).
    - Create a subfolder for motion data (“\sid1001\motion”)
    - Make the optotrak session name “sid####” to match the folder name

- Record the session filename, or an example filename after the first trial is saved, on the datasheet (long name, includes the time that the session was started…)

3. 12 Markers, 30 Hz
   Use rigid body "biodynamicsprobe.rig" as first six markers
4. Plug the probe into Optotrak cable first, followed by the strober for the foot markers (daisy chain).
5. Conduct 3- second trials to probe the needed points: *Make sure visibility is near 100%
   - Lateral Maleolus (middle of LM)
   - Medial maleolus (middle of MM)
   - Toe tip (farthest anterior, as close to floor contact point as possible)
   - 2nd metatarsal (feel for the 2nd toe)
   - heel (farthest posterior, near floor contact point)
   - heel (anatomical heel, in the middle of the back of the shoe).

6. Conduct 30 second trials to probe foot perimeter. Start trial, then drag probe tip around foot. Do not lose contact w/ foot. Try to get as good vis as possible, but 100% is obviously impossible.
7. Record file numbers for all probe trials on the datasheet

Analog DAQ setup

1. if not already done, create a subject data folder on the analog DAQ computer ("\data\sid####\").
2. Start the labview program "data_collection_whitenoise.vi" on the DAQ computer. It is under a root directory with the same file path name as the other computer.
3. Double check that the physical channels selected are analog 0:11, 16:21, and 28:30. This should be the default.
4. Sample rate: 1000
5. Collection time: 4

Analog Zero Trial

1. Be sure thing is sitting on the forceplates. Rope should not be attached to lean/release mechanism
2. On the "data_collection_whitenoise.vi" front panel, switch "use trigger" to "off".
3. Click run arrow.
4. After collection has run, a dialog box will ask you to pick a filename. Save the trial as "zero" under the subject's data directory.
5. Switch "USE TRIGGER" to "ON". You will use the trigger for all trials from here on out.

Lean Angle Monitor setup

1. Start "lean_angle_monitor.vi" on the analog daq computer. (under same root directory as everything else…)

2. under “zero trial location” enter the file location / name of the zero trial you just took.
3. Forceplate channels should be 0:11
4. Don’t worry if you get crazy lean angles when subject is not standing on the plate. This is expected. If lean angle is obviously not correct when subject IS on plate, check that the zero trial was conducted properly, and zero trial filename are right.

Lean & Release Trials

*do once at the beginning of the lean & release trials:

1. Start a new Optotrak experiment. Use 6 markers, 100 samples per second. 4-second trials. Record session name on the datasheet.

2. Attach ceiling harness
    - Adjust tension on ceiling harness such that the harness becomes taut when the subject stands on the front forceplate and bends their knees to a 90 deg angle
    -
3. read instructions lean & release overview
4. Have subject stand facing away from Lean/release mechanism, feet shoulder width apart on fp1 & fp2.
    - toes should just touch taped line

5. Tape the lateral foot starting positions so that the position can be repeated for each trial
6. Turn off the main room lights (safety light in the corner will stay on—this is OK.)
7. Read instructions for the trial that will be conducted.

*For each lean and release trial:

8. If there will be a target presented for the trial:

   -Ensure that the target light is turned on. If not, the light switch on the table may need to be clicked “on”.

   -In “control.vi” click “find home”. Target should return to the center of the front bolts on forceplate 3. If it does not, try again. If it still doesn’t find home, it may not be warmed up. If it is warm and doesn’t find home, you may have to move the cart so that the home position is properly lined up with the bolts.

   -Decide where the target should be in terms of percent bodyheight (consult the detailed description of the sequence for the block of trials you are currently conducting).

   - Consult the steplengths list table you’ve already generated. Note the number of steps from home that the stepper motor must move in order to position the target where you want it.

   -Record number of steps for the next trial on the testing datasheet

-Move the target the appropriate number of steps forward by entering a number on the “control.vi” and clicking “initiate movement”. If you need to move the target more than 63 steps forward, you may need to perform the movement in several smaller movements (for example, to move 103 steps, you might move 50 steps, then another 53).

9. Attach rope. Have subject lean.
10. Monitor lean angle with “lean_angle_monitor.vi”.
    -Adjust rope length until lean angle is 10 ± 0.5 degrees

11. Stop “lean_angle_monitor.vi”. click “wait for trigger” in Optotrak. Start “data_collection_whitenoise.vi”.
    -you MUST stop lean_angle_monitor.vi before starting data collection.
12. When Labview random time delay is up, green light on front panel will come on. You can now activate trigger to run the trial.
13. After each trial, record target position (in number of steps moved by stepper motor), analog filename, optotrak file number (only need to note the full file prefix for each block of trials on the right side of the datasheet), and number of steps taken.
    -Only count as two steps if 2nd step advances past first step. If it obviously picks up and then puts down (but does not advance past 1st step), mark as 1.5 steps.

Conduct the following 3 blocks of trials.

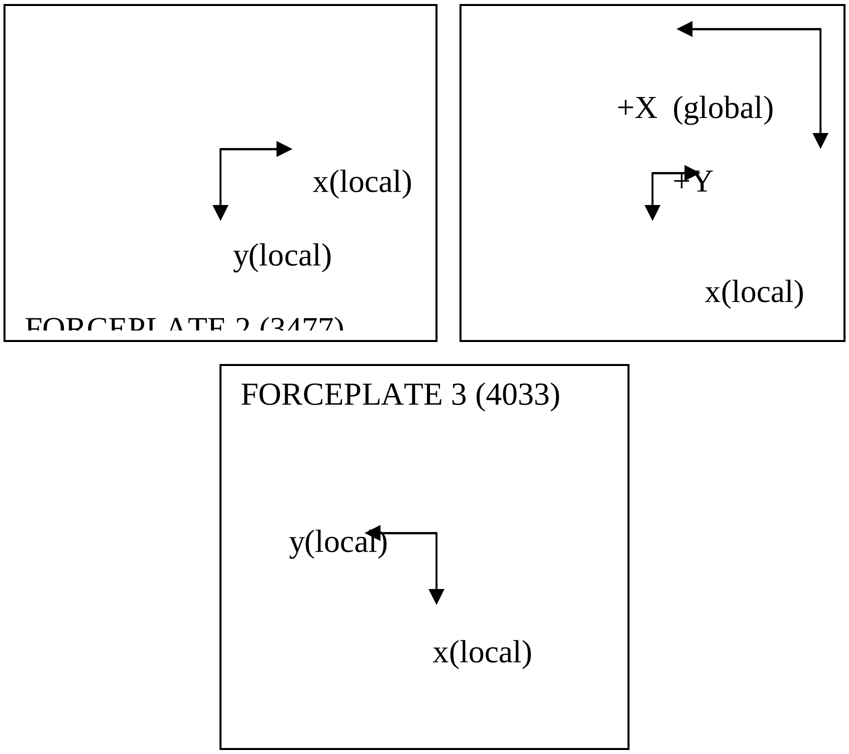
- I. Natural Response
  - a. 6 total
- II. Targeted Natural Response
  - a. Give instructions
  - b. Warmup
    - i. Do each length until subject successfully places first step short of line and regains their balance. Repeat as needed.
      1. 30%
      2. 23%
      3. 15%
  - c. Start downward leg
    - i. Start @ 30% BH
    - ii. Increment down 2% BH after each single step
    - iii. Repeat if step is over the line
    - iv. Repeat if multiple steps are taken
    - v. Stop when 2 consecutive multiple steps are taken
    - vi. FAILURES: (harness or steplength)
      1. Repeat position if there is a failure

            a. Inform subject if it is a step length failure, do not inform if harness failure.
        2. If 2 consecutive failures, STOP DOWNWARD LEG
        3. If 1 failure is followed by multiple step, repeat that step length and treat (for protocol purposes) as if the failure did not happen.
  d. Start upward leg
    i. Start @ 8% BH LESS than where we stopped on downward leg or 8% BH, whichever is greater.
    ii. Increment up 2% BH after each multiple step
    iii. Repeat if step is over the line
    iv. Repeat if single step is taken
    v. Stop when 2 consecutive single steps are taken.
    vi. FAILURES: (harness or steplength)
        1. Repeat position is there is a failure
            a. Inform subject if steplength failure, do not inform if harness failure
        2. If 2 consecutive failures, increment up 2% BH
        3. If 1 failure is followed by a single step, repeat that step length and treat (for protocol purposes) as if the failure did not occur.

III. Targeted Single Step Response
  a. Give instructions
  b. Start downward leg
    i. Start @ 30% BH
    ii. Increment down 2% BH after each single step
    iii. Repeat if step is over the line
    iv. Repeat if multiple steps are taken
    v. Stop when 2 consecutive multiple steps are taken.
    vi. FAILURES: (harness or steplength)
        1. Repeat position if there is a failure
            a. Inform subject if it is a step length failure, do not inform if harness failure.
        2. If 2 consecutive failures, STOP DOWNWARD LEG
        3. If 1 failure is followed by multiple step, repeat that step length and treat (for protocol purposes) as if the failure did not happen.
  c. Start upward leg
    i. Start @ 8% BH less than where we stopped on downward leg, or 8% BH, whichever is greater
    ii. Increment up 2% BH after each multiple step
    iii. Repeat if step is over the line
    iv. Repeat if single step is taken
    v. FAILURES: (harness or steplength)

1. Repeat position is there is a failure
    a. Inform subject if steplength failure, do not inform if harness failure
2. If 2 consecutive failures, increment up 2% BH
3. If 1 failure is followed by a single step, repeat that step length and treat (for protocol purposes) as if the failure did not occur.

Stop when 2 consecutive single steps are taken.



*Force plate serial numbers and orientation

Instructions to be read to participants:

OVERVIEW:

"For today's tests, we will attach one end of this rope to back of the belt that you are wearing. The other end will be attached to this machine. When I ask you to lean forward, you will lean until your weight is supported by the rope. You will stand with your arms across your chest. While leaning into the rope, try to relax your ankles as much as possible. You may be asked to maintain this position for a short time while we ready our equipment. We will tell you when the test is about to begin. A few seconds after the test begins, the rope will be released, and you will respond naturally to regain your balance. Any questions?"

SETTING UP THE LEAN:

"Stand with your toes just touching the taped line. Please lean into the rope. This may take a moment while we get our equipment ready."

"Remember to relax your ankles."

IF THE ROPE NEEDS ADJUSTED:

"I'm going to help you stand back up so that we can make an adjustment to the rope."

Experiment #1: Natural Response
READ ONCE:
"When I say 'the test will begin', please cross your hands crossed in front of your chest. Several seconds after you have been given the ready cue, the rope will be released. Respond naturally in order to regain your balance. You may choose to take one or more steps to regain your balance. Once you have regained your balance, stand still until I instruct you to relax."

BEFORE EACH TRIAL:
"Please hold your arms across your chest and relax your ankles. The test will begin now."

Experiment #2: Targeted response
READ ONCE:
"For this set of tests, a red line will be projected onto the floor in front of you. When I say 'the test will begin', please cross your hands in front of your chest. Several seconds after you have been given the ready cue, the rope will be released. Respond naturally in order to regain your balance. You may take one or more steps to regain your balance, but in both cases, the first step should not cross over the red line. If your first step crosses over the line, the trial will be repeated. Once you have regained your balance, stand still until I instruct you to relax."

BEFORE EACH TRIAL:
"Remember not to step over the target line with your first step. Please hold your arms across your chest and relax your ankles. The test will begin now."

--
IF SUBJECT STEPS OVER LINE:
"Since your first step crossed over the line, this trial will be repeated."
Experment #3: Single step targeted response

READ ONCE:
For this set of tests, a red line will be projected onto the floor in front of you. When I say 'the test will begin', please look cross your hands in front of your chest. Several seconds after you have been given the ready cue, the rope will be released. Attempt to regain your balance by taking only one step. The step should not cross over the red line. If your step crosses over the line, the trial will be repeated. Do not take more

than one step unless you must to regain your balance. Once you have regained your balance, stand still until I instruct you to relax.”

BEFORE EACH TRIAL:
“Try to regain your balance with only one step. Remember not to step over the target line. Please hold your arms across your chest and relax your ankles. The test will begin now.”

IF SUBJECT TAKES 2 STEPS:
Please remember not to take more than one step unless you must to regain your balance.

IF SUBJECT STEPS OVER LINE:
“Since your first step crossed over the line, this trial will be repeated.”

Subject testing datasheet: page 1:

Subject Number:

Date:

MEASUREMENTS

Bodyweight		
Height		

Leg Length	L		R	
Ankle Width	L		R	
Ankle Height	L		R	
Foot Width	L		R	
Foot Length	L		R	

Rope Height		

Datasheet page 2:

Subject Number:
Date:

Record all Optotrak data on the Optotrak computer under the folder
C:\Documents and Settings\Biodynamics Lab\My Documents\mch\leanandrelease_study\data\sid…

Record all analog data on the analog DAQ computer in the folder
C:\Documents and Settings\Biodynamics Lab\My Documents\mch\leanandrelease_study\data\sid…
*In Optotrak, use subject number in the session name, as in "sid…"

	Motion file number	Analog file number
Analog Zero	▨	
	▨	▨
Lateral Maleolus, RIGHT		▨
Medial Maleolus, RIGHT		▨
2nd Metatarsal, RIGHT		▨
Toe tip, RIGHT		▨
Heel (ground level), RIGHT		▨
Heel (anatomical), RIGHT		▨
	▨	▨
Lateral Maleolus, LEFT		▨
Medial Maleolus, LEFT		▨
2nd Metatarsal, LEFT		▨
Toe tip, LEFT		▨
Heel (ground level), LEFT		▨
Heel (anatomical), LEFT		▨
	▨	▨
Foot Perimeter RIGHT		
Foot Perimeter LEFT		

Datasheet page 3:

Subject Number:

Date:

NATURAL RESPONSE

	Target position	Motion file #	Analog file #	steps taken	Optotrak session, Notes
1					
2					
3					
4					
5					
6					
7					

Datasheet page 4:

Subject Number:	
Date:	

TARGETED RESPONSE

Practice

	Target position	Motion file #	Analog file #	steps taken	Optotrak filename.	Notes
1						
2						
3						
4						
5						
6						
7						
8						

Downward Leg

	Target position	Motion file #	Analog file #	steps taken	Optotrak filename.	Notes
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						

Upward Leg

	Target position	Motion file #	Analog file #	steps taken	Optotrak filename.	Notes
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						

Datasheet page 5:

Subject Number:
Date:

SINGLE STEP TARGETED RESPONSE

Downward Leg

	Target position	Motion file #	Analog file #	steps taken	Optotrak filename, Notes
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Upward Leg

	Target position	Motion file #	Analog file #	steps taken	Optotrak filename, Notes
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

ANALOG CHANNELS

All analog channels were sampled on the a/d board at 1000 Hz using the custom Labview VI “data_collection_whitenoise.vi”. Channels sampled were as follows:

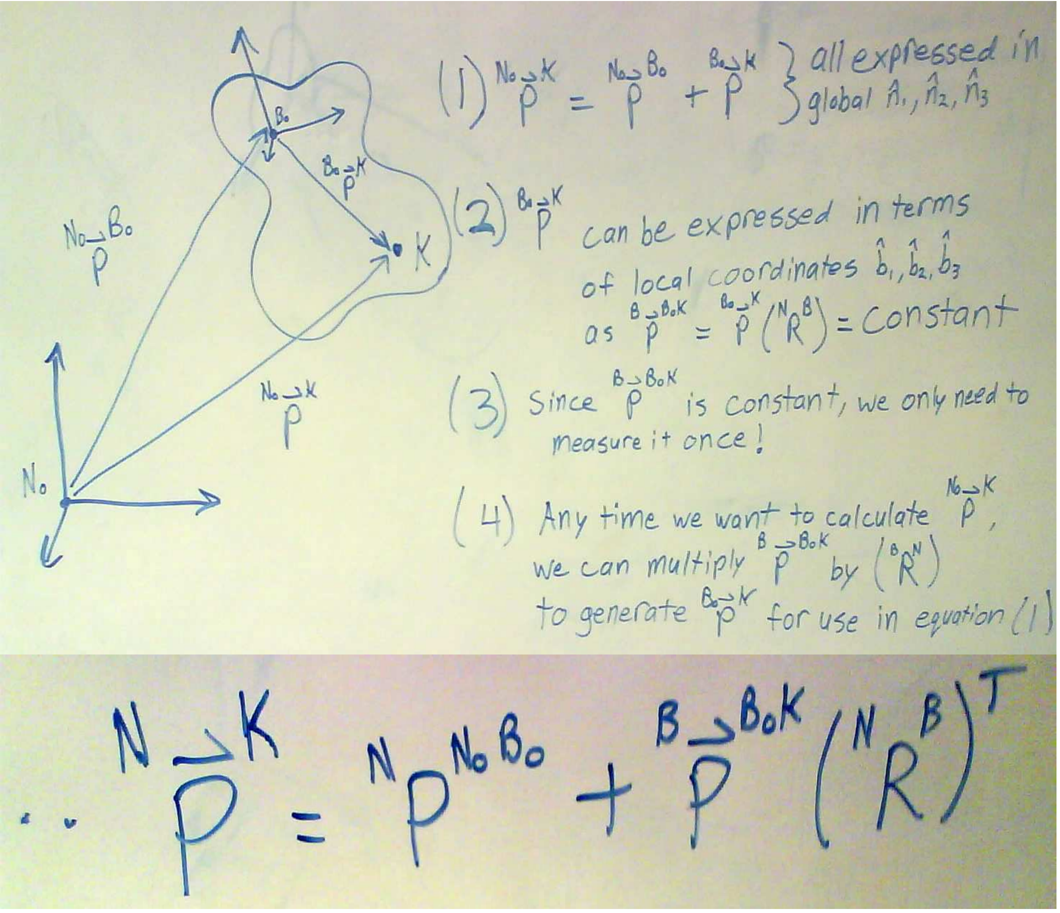
input channel #	data column #	description	ground switch	notes
0	1	FP1 (Fx)	up	*FOR ALL FORCEPLATE CHANNELS:
1	2	FP1 (Fy)	down	gain = 1000
2	3	FP1 (Fz)	down	Low pass filter = 1050 Hz
3	4	FP1 (Mx)	down	These directions (x,y,z) are forceplate local coordinates
4	5	FP1 (My)	down	"forceplate converter" rotates into room coordinates
5	6	FP1 (Mz)	down	
6	7	FP2 (Fx)	up	
7	8	FP2 (Fy)	down	
8	9	FP2 (Fz)	down	
9	10	FP2 (Mx)	down	
10	11	FP2 (My)	down	
11	12	FP2 (Mz)	down	
16	13	FP3 (Fx)	up	
17	14	FP3 (Fy)	down	
18	15	FP3 (Fz)	down	
19	16	FP3 (Mx)	down	
20	17	FP3 (My)	down	
21	18	FP3 (Mz)	down	
28	19	L&R Loadcell	up	
29	20	Harness Loadcell	up	
30	21	Switchplate	up	Low normal, goes high (+9) when plate is loaded

APPENDIX B: MOTION ANALYSIS

A virtual marker method was used to track the location of anatomical landmarks upon which infrared markers were not attached. Prior to each testing session, a three-marker rigid body was attached to the top of each participant's foot. This rigid body defined a local foot coordinate system in terms of a vector (in global coordinates) to an origin, and a rotation matrix to rotate the local coordinate system into the global.

During static trials, anatomical landmarks (e.g., toe, heel) were probed with an Optotrak rigid body tool, and the vector (in local coordinates) from the origin of the foot coordinate system to each landmark was calculated. Thereafter, the location of the landmark could be computed by measuring the location and orientation of the foot coordinate system and applying the method outlined in the following figure.

Notes on computing the location of virtual marker (K) given a local vector (${}^{Bo}p^{K}$) from a rigid body whose position (${}^{No}p^{Bo}$) and orientation (${}^{N}R^{B}$) are known.



(1) ${}^{N_o}\vec{p}^{K} = {}^{N_o}\vec{p}^{B_o} + {}^{B_o}\vec{p}^{K}$ } all expressed in global $\hat{n}_1, \hat{n}_2, \hat{n}_3$

(2) ${}^{B_o}\vec{p}^{K}$ can be expressed in terms of local coordinates $\hat{b}_1, \hat{b}_2, \hat{b}_3$ as ${}^{B}\vec{p}^{B_oK} = {}^{B_o}\vec{p}^{K}({}^{N}R^{B}) =$ constant

(3) Since ${}^{B}\vec{p}^{B_oK}$ is constant, we only need to measure it once!

(4) Any time we want to calculate ${}^{N_o}\vec{p}^{K}$, we can multiply ${}^{B}\vec{p}^{B_oK}$ by $({}^{B}R^{N})$ to generate ${}^{B_o}\vec{p}^{K}$ for use in equation (1)

$$. . \quad {}^{N}\vec{p}^{K} = {}^{N}p^{N_oB_o} + {}^{B}\vec{p}^{B_oK}\left({}^{N}R^{B}\right)^{T}$$

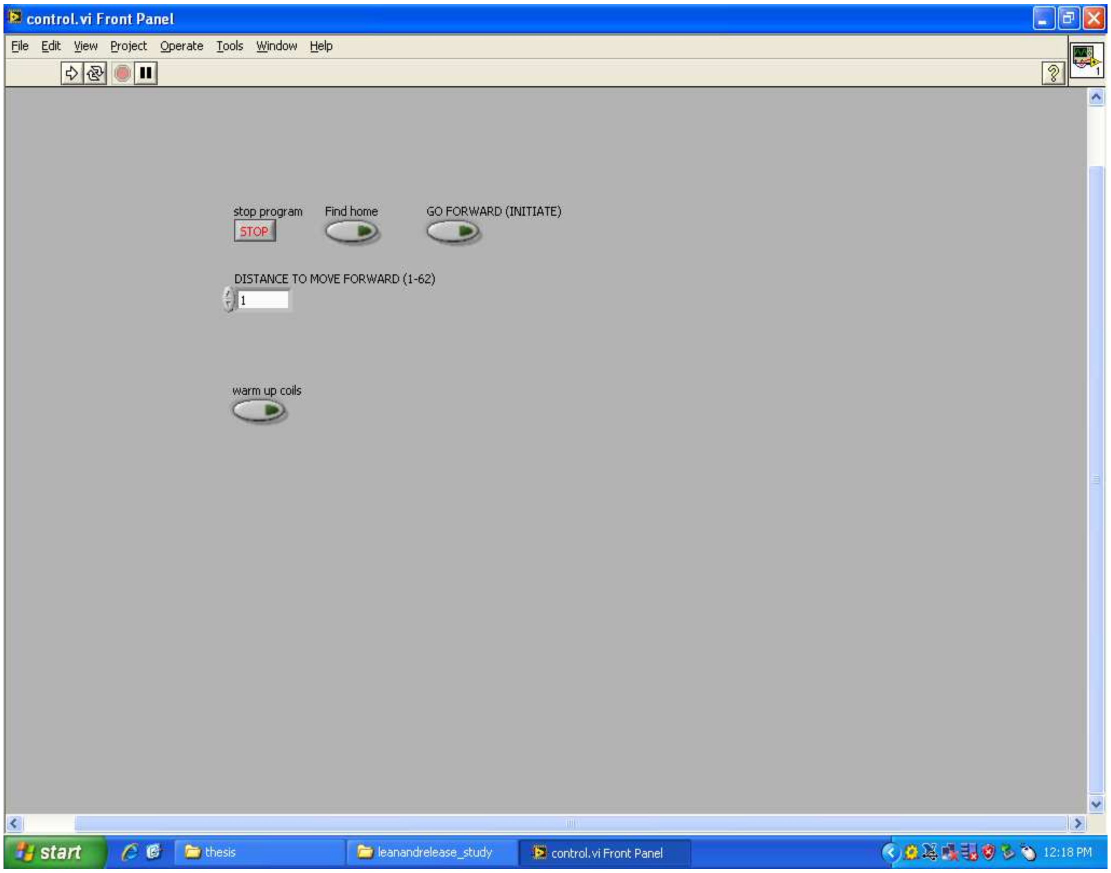
APPENDIX C: BOUNDARY LINE PROJECTION SYSTEM

A novel boundary line positioning system was designed to allow accurate computer control of the projection of a laser line onto the floor. An auto-leveling commercial laser level (Black and Decker, USA) generated the horizontal boundary line. However, in order to eliminate vibration-induced movement of the laser, the auto-leveling feature was disabled by freezing the pendulum with a two-part adhesive.

The line was reflected downward from the horizontal by a front-surface mirror that was mounted to a rotary positioning turntable (Daedal, PA, USA). A stepper motor (Oriental Motor Company, Japan) turned the positioning table’s worm gear. The stepper motor was driven by a Parallax BS2 microcontroller connected through a series of transistors and solid-state relays to isolate the microcontroller from the stepper motor power source. The coils were energized in a half-step mode sequence as this was observed to decrease vibration and result less frequently in missed steps.

A custom Labview interface allowed the mirror to be positioned from a desktop computer. Eight digital outputs of the NI board were used to communicate between the computer and a Parallax BS2 microcontroller. Six of the digital outputs set the distance to move the stepper motor (in number of steps), one output initiated movement, and another commanded the microcontroller to initiate a search for the rotary turntable’s home position.

Since the experimental protocol called for the target to be positioned a given percentage of the participant’s body height in front of the toe starting position, a series of calibration calculations were employed. Prior to the first testing session, and periodically throughout the course of the experiment, the boundary position at various stepper motor positions was digitized in the room coordinate system using an Optotrak digitization tool. For each subject, a Matlab m-file was run which loaded the most recent set of digitized coordinates and used a least squares fit to compute a third order polynomial relating stepper motor position to target line position. Then, the subject’s height was entered and the target line’s absolute position was converted to percent body height in front of the taped toe line. A table was generated that related boundary locations, in percent body height, to the stepper motor position needed to achieve that target location. This table was referenced prior to each trial in order to set the correct target location.



DISTANCE TO MOVE FORWARD (1-62): 1

LabVIEW interface used to control the target position. The user enters the appropriate number of steps to move the target (determined from the Matlab-generated position table) and pushes the “Go Forward” button to initiate the movement.

POSITIONS TABLE

using calibrations from C:\Documents and Settings\Biodynamics
Lab\My
Documents\mch\leanandrelease_study\data\calibration_09_19_08
for subject number ###
with body height = 177 cm

Steplengths, %bh	nsteps
30	38
29	44
28	50
27	56
26	62
25	68
24	74
23	80
22	86
21	91
20	97
19	103
18	108
17	114
16	119
15	125
14	130
13	135
12	141
11	146
10	151
9	156
8	161
7	166
6	171
5	176
4	181

Typical subject-specific positions table relating available step length (boundary location) to the number of steppermotor steps needed to position the laser appropriately.

LASER CALIBRATION PROTOCOL

Periodically throughout the experiment, the position of the projected boundary line was established in global coordinates. This involved moving the boundary line a set number of stepper motor steps from its “home” position (as sensed by a magnetic Hall effect sensor on the rotary turntable), and measuring its position using the Optotrak rigid body probe. The protocol for performing this calibration, and datasheet onto which file information was recorded, are included here. The numerical calibration was performed prior to each testing session when the subject-specific boundary position table was generated.

Laser line warm up / calibration

1. Turn on laser, stepper motor power, and start “control.vi”.
2. Ensure that laser returns to “home” properly (should return to the middle of the front bolts on fp3)
3. Step the target forward 200 steps in 50-step increments. Mark the end position
4. Return home
5. Step the target forward 200 steps in 10-step increments. Ensure that the position is the same as in (2), when 50-step increments were used.

If check #1 or #4 fails, the coils may not be warm. Click the “warm up coils” button on the control.vi front panel. You should hear clicking from the stepper motor. Allow warmup to occur for ten minutes, and then try 1-4 again.

Set up Optotrak coordinate system according to standard procedure. Origin is at the dot on the NE corner of FP1, +X points West, and +Z is up.

Probe a spot on the line near the centerline of the forceplates for laser locations (in # steps from home) listed on the calibration_datasheet. Record the optotrak file numbers on the blank_calibration_datasheet, and save the datasheet.

Laser calibration datasheet

Date:	
nsteps_from_home	filenum
0	
20	
40	
60	
80	
100	
120	
140	
160	
180	
tapefront	
fp1center	
fp2center	
fp3center	

Datasheet where filenames were recorded during boundary calibration. A copy of this datasheet was saved on the computer's hard drive and used in generating the participant-specific boundary positions table.

PBASIC CODE FOR CONTROLLING THE BOUNDARY POSITION

```
' {$STAMP BS2}
' {$PBASIC 2.5}
‘Pbasic code
‘stepper_driver_2_halfsteps.bs2
‘Michael Haines
'Communicates with Labview VI "control.vi" to control laser target position with a
‘stepper motor.

dt VAR Word
steps VAR Word
stepstaken VAR Word
i VAR Word
moveto VAR Byte
homeoffset VAR Byte
counter VAR Nib
lastdirection VAR Bit



homeoffset = 144    'Distance from magnetic home switch to the force plate bolts
(recognizable 'home position), found by trial and error




lastdirection = 0
counter=1
i=0
'dt = 15
dt = 7
stepstaken=0

homesense PIN 14
INPUT homesense
initiate PIN 6    'pin 6 and 7 are from NI board digital outputs
INPUT initiate
movehome PIN 7

start:

DO

DO WHILE initiate=0
```

```
  'DEBUG HOME
  'DEBUG DEC dt
  'GOSUB powerup
  IF movehome=1 THEN
    GOSUB findhome   'Initiate sequence to find home position
    PAUSE 1000
  ENDIF

  moveto = (IN8) + (IN9*2) + (IN10*4) + (IN11*8) + (IN12*16) + (IN13*32)
'Number of steps to cycle the stepper

  IF moveto = 63 THEN         'Using one of the moveto options for an additional
command, to warm up the coils
    steps = 7
    GOSUB forward
    DO WHILE ((IN8) + (IN9*2) + (IN10*4) + (IN11*8) + (IN12*16) + (IN13*32)) =
63
        GOSUB warmup         'Do the warmup routine
    LOOP
  ENDIF


  'otherwise do nothing

LOOP


moveto = (IN8) + (IN9*2) + (IN10*4) + (IN11*8) + (IN12*16) + (IN13*32)

steps = moveto*2

GOSUB back
'after forward movement, make sure it stays put for a sec
PAUSE 500



LOOP




'--------------------------------------
'zero means we're in the home range
```

```
'we want to back in to home range

findhome:
steps=5
DO WHILE homesense = 0
  GOSUB back
LOOP

steps=30
GOSUB back

steps=1
DO WHILE (homesense = 1)
  GOSUB forward
LOOP

steps=homeoffset
GOSUB back

RETURN

'-----------------------------------------------------



forward:

'sequence:  2,24,4,34,3,35,5,25
stepstaken=0
DO
   DEBUG CLS
DEBUG HOME
DEBUG DEC homesense
  IF stepstaken>steps-1  THEN RETURN

  counter=counter+1
  IF counter=9 THEN counter=1

                         'This is the sequence of pins that must be fired
                         'to move forward by half steps
  IF (counter = 1) THEN  GOSUB fire2

  IF (counter = 2) THEN GOSUB fire24
```

```
  IF (counter = 3) THEN  GOSUB fire4

  IF (counter = 4) THEN  GOSUB fire34

  IF (counter = 5) THEN  GOSUB fire3

  IF (counter = 6) THEN GOSUB fire35

  IF (counter = 7) THEN GOSUB fire5

  IF (counter = 8) THEN GOSUB fire25


  stepstaken=stepstaken+1               'loop until we've taken the appropriate number of
steps

LOOP


RETURN


'----------------------------------
back:
'sequence is:  5,3,4,2
stepstaken=0



DO
DEBUG CLS
DEBUG HOME
DEBUG DEC homesense
  IF stepstaken>steps-1 THEN RETURN
  counter=counter-1
  IF counter=0 THEN counter=8

  IF (counter = 1) THEN  GOSUB fire2           'firing sequence to step backward by
half steps

  IF (counter = 2) THEN GOSUB fire24

  IF (counter = 3) THEN  GOSUB fire4
```

```
  IF (counter = 4) THEN  GOSUB fire34

  IF (counter = 5) THEN  GOSUB fire3

  IF (counter = 6) THEN GOSUB fire35

  IF (counter = 7) THEN GOSUB fire5

  IF (counter = 8) THEN GOSUB fire25


  stepstaken=stepstaken+1


LOOP

warmup:

GOSUB fire24                          'Just energize pairs of coils to get them warm
PAUSE 250
GOSUB fire34
PAUSE 250
GOSUB fire35
PAUSE 250
GOSUB fire25
PAUSE 250
GOSUB fire35
PAUSE 250
GOSUB fire34
PAUSE 250

RETURN





'------------------------------------
'Subroutines to energize the stepper coils
fire2:
LOW 3
LOW 4
LOW 5
```

```
HIGH 2
PAUSE dt
RETURN

fire3:
LOW 2
LOW 4
LOW 5
HIGH 3
PAUSE dt

RETURN


fire4:
LOW 2
LOW 3
LOW 5
HIGH 4
PAUSE dt
RETURN

fire5:

LOW 2
LOW 3
LOW 4
HIGH 5
PAUSE dt
RETURN


fire24:
LOW 5
LOW 3
HIGH 2
HIGH 4
PAUSE dt
RETURN

fire34:
LOW 2
LOW 5
HIGH 3
```

```
HIGH 4
PAUSE dt
RETURN


fire35:
LOW 2
LOW 4
HIGH 3
HIGH 5
PAUSE dt
RETURN

fire25:
LOW 3
LOW 4
HIGH 2
HIGH 5
PAUSE dt
RETURN

powerup:
HIGH 2
HIGH 3
HIGH 4
HIGH 5
RETURN

powerdown:
LOW 2
LOW 3
LOW 4
LOW 5
RETURN
```

APPENDIX D: DATA PLOTS

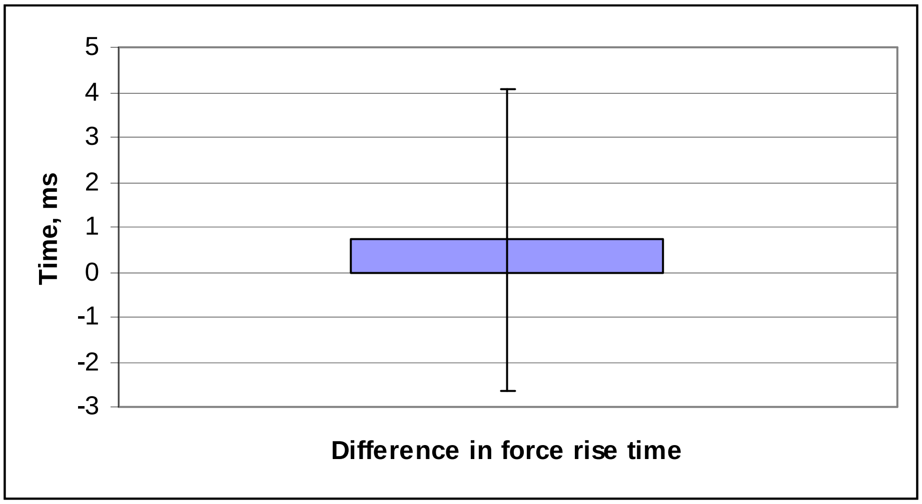


Figure D1. Average difference in force rise time between multiple step and single step recoveries. Positive value indicates a slightly later, but statistically nonsignificant, force rise time during multiple stepping. N=7.

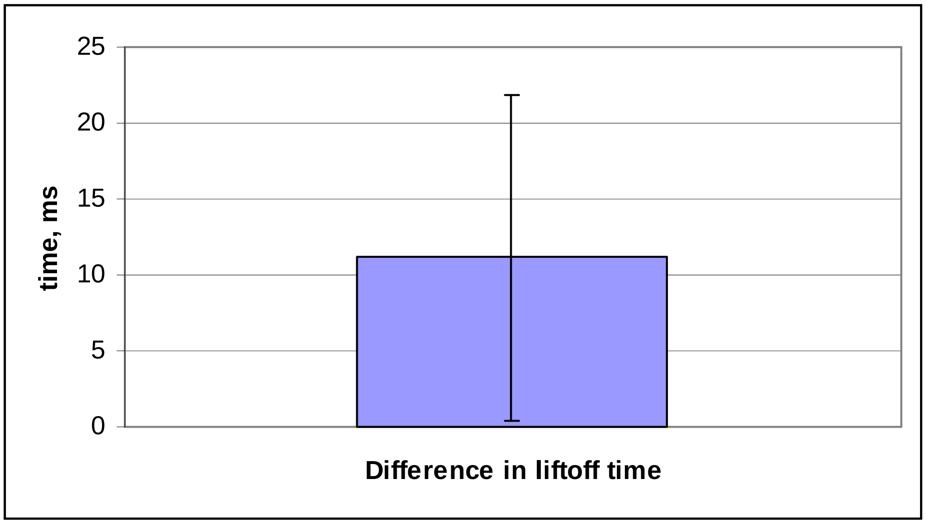


Figure D2. Average difference in liftoff time between multiple and single step responses. Positive value means liftoff occurred significantly later (p<.05) during multiple stepping. N=7.

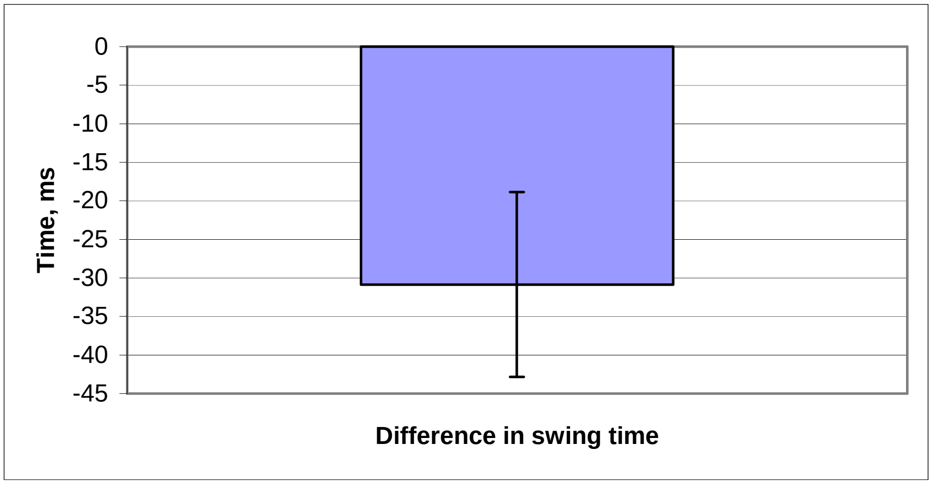


Figure D3. Average difference in swing time between multiple and single step responses. Negative value indicates significantly shorter swing time during multiple steps (p<.001). N=7.

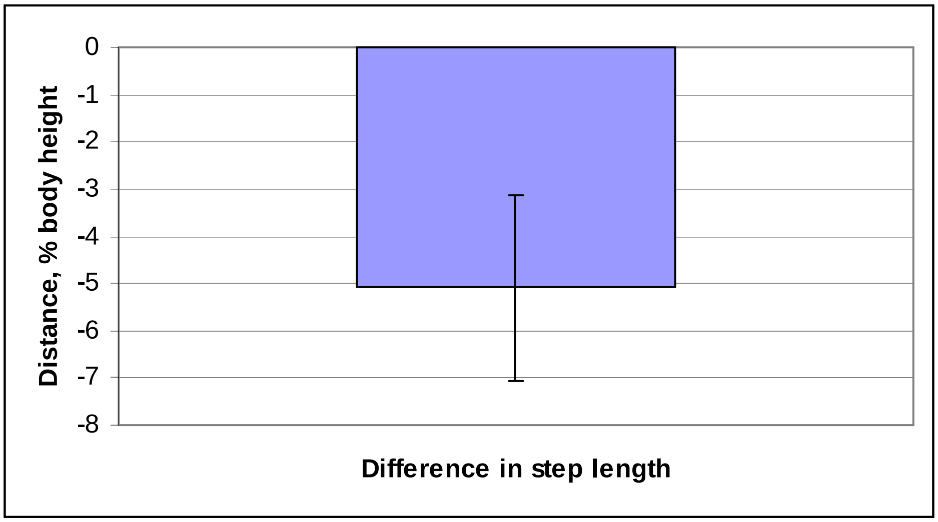


Figure D4. Average difference in first step length between multiple and single step responses. Negative value indicates significantly shorter first step length during multiple stepping (p<.001). N=7.

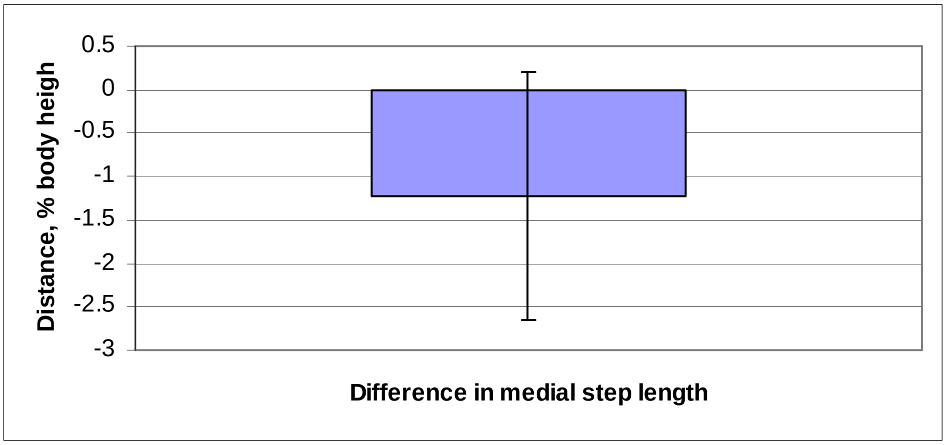


Figure D5. Average difference in medial step length between multiple and single step responses. Negative value indicates a smaller (but not statistically significant) movement of the stepping foot towards the midline of the body during multiple stepping. N=7.

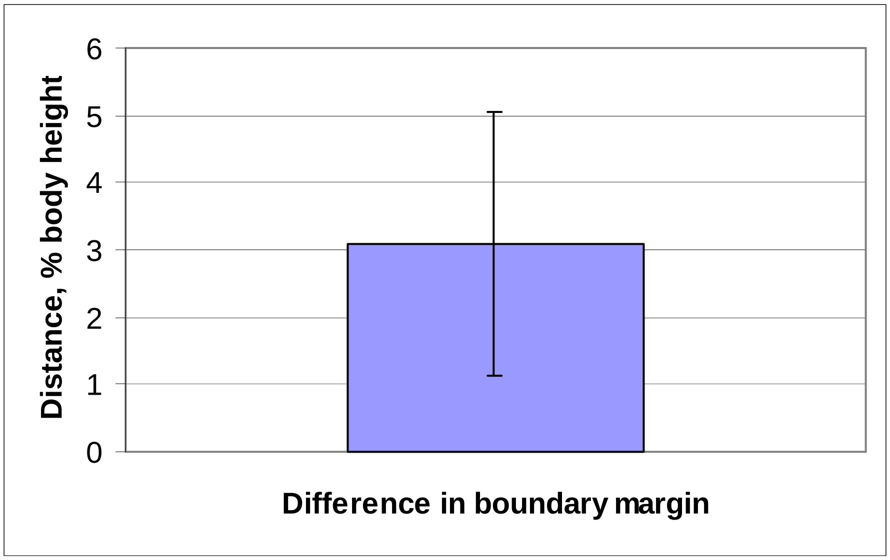


Figure D6. Average difference in step length boundary margin between multiple and single step responses. Positive value indicates larger boundary margin during multiple stepping (p<.01). N=7.

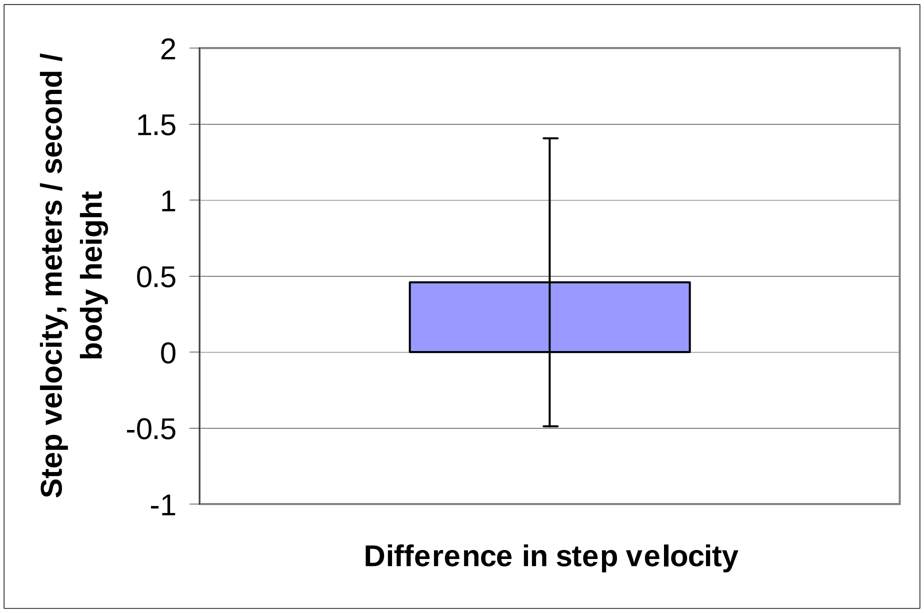


Figure D7. Average difference in step velocity between multiple and single step responses. Positive value indicates higher (but not statistically significant) step velocity during multiple stepping. N=7.

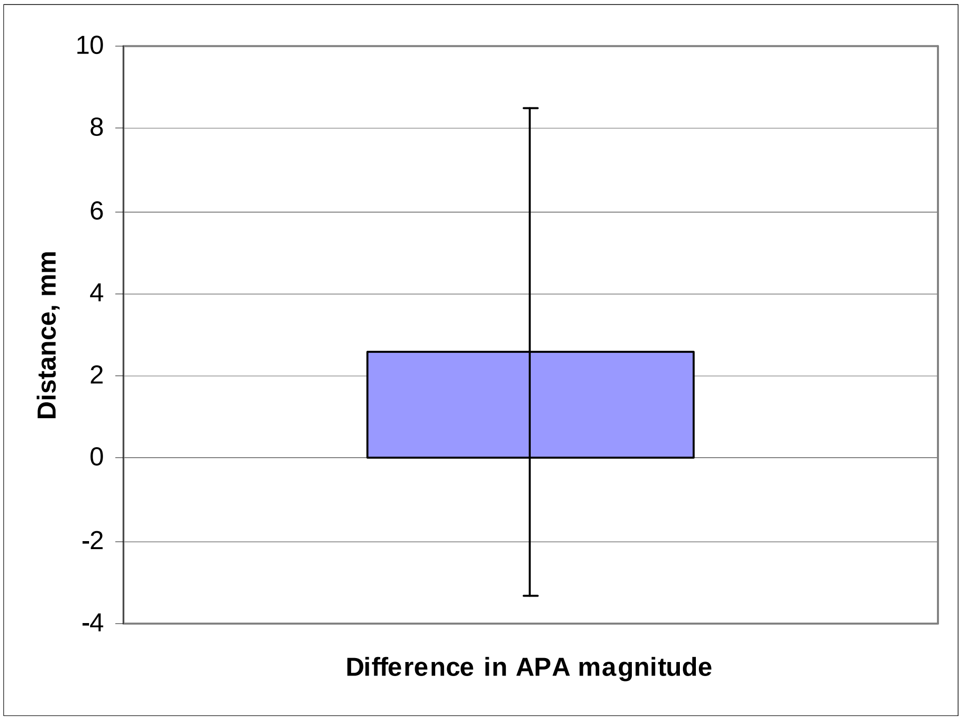


Figure D8. Average difference in anticipatory postural adjustment magnitude between multiple and single step responses. Positive value indicates slightly larger (though not statistically significant) APA magnitude during multiple stepping. N=7.

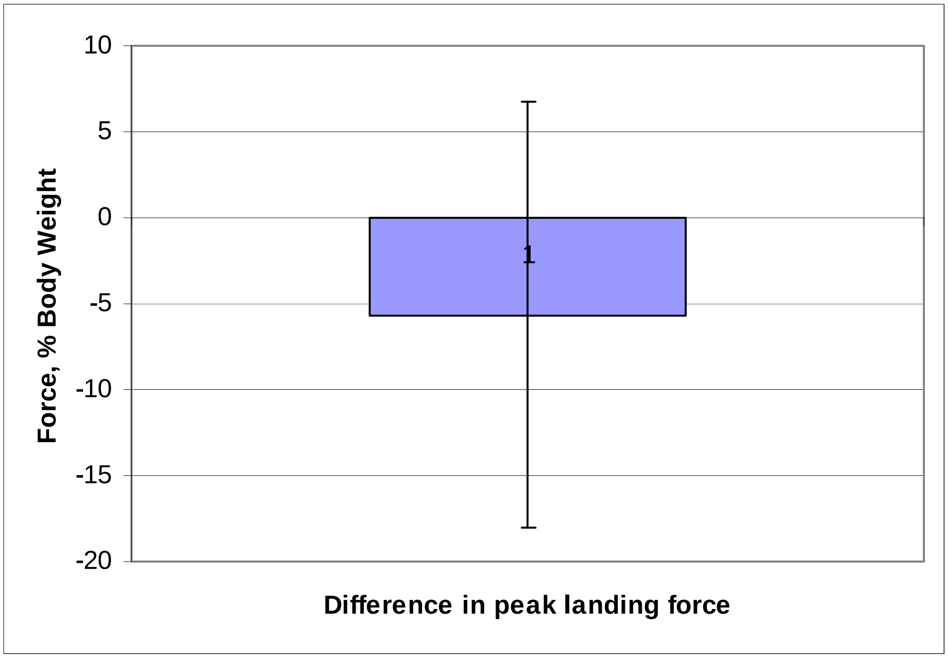


Figure D9. Average difference in peak landing force between multiple and single step responses. Negative value indicates smaller (but not statistically significant) landing forces during multiple stepping. N=7.

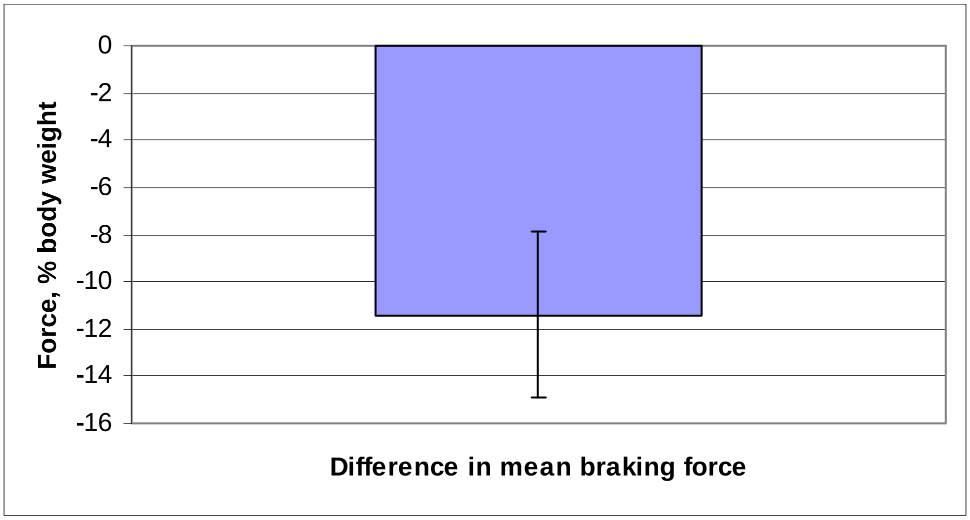


Figure D10. Average difference in mean braking force during 100ms following landing of the first step between multiple and single step responses. Negative value indicates less braking during multiple stepping ($p<.001$). N=7.