The Report Committee for Kelly Anne Frank

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Dynamic Stability during Perturbed Human Walking

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Dynamic Stability during Perturbed Human Walking

by

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Report

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Abstract

Dynamic Stability during Perturbed Human Walking

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The recovery strategies after a trip vary depending on several conditions. The location, timing, and magnitude of the trip are determining factors as well as the speed of the subject when the trip occurs. Previous studies focused on the trip and the recovery without systematically varying the walking speed. Individuals at high risk of falls alter their walking speed in an effort to be more stable in case of a trip. However, no studies to date have analyzed the recovery strategies when walking faster and slower than preferred. Using a treadmill and a specially designed tripping device allows for subjects to be unsuspectingly tripped at different times and different speeds while measuring kinematic and EMG responses. The tripping device included a cuff attached to the left ankle of the subject and would stop the left ankle when signaled by the experimenter. From these findings we can infer that slower walking does aid in trip recovery. Although a more robust study should be performed to confirm the consistency of these findings across multiple populations, it seems that slower walking does aid in trip recovery.

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Chapter One: Introduction

1.1 Background and Significance

Falls pose a significant risk to the elderly population, including physical, emotional, and financial repercussions. Physical injury can limit an elderly individual's future mobility and sometimes the fall can even result in death. The emotional turmoil resulting from a fall frequently causes elderly individuals to become reclusive, refusing to risk another potential fall. The cost to treat the injuries resulting from these falls exceeded $19 billion in 2000 [Stevens et al., 2006] and a trip is the initial cause of 53% of the falls in the elderly population [Blake et al., 1988]. One in every three adults, aged 65 and older, falls each year [Hausdorff et al., 2001] and given the large costs resulting from these falls, the relationship between trips and falls has been a focus of study for years. However, the results have been highly varied and sometimes inconclusive. A predicative measure of trip recovery and falls is a necessary and valuable tool for the elderly, at risk population. If we can predict trip response and an individual's risk of falling, could we prevent them?

1.2 Previous Research / Predictive Measures of Fall Risk

Previous studies have focused on several measures to predict the risk of falls in the elderly, including minimum toe clearance, timed up and go, various kinematic, and stability measures.

1.2.1 Minimum Toe Clearance

Minimum toe clearance (MTC) is defined as the distance between the ground and the toe during the swing phase of the gait cycle. This is a critical event in walking because the foot is also travelling with maximum horizontal velocity at the same point in time the toe is at its minimum clearance with the ground. In the study by Begg (2007), 17 young female and 16 elderly female participants were instructed to walk on a treadmill at their

self- selected pace. Kinematics were measured in order to calculate their MTC. Results indicated that the elderly participants had significantly slower preferred walking speeds than the young participants and lower median MTC. However, the MTC differences when compared between young participants and elderly participants were not significant [Begg et al., 2007]. Begg then partnered with Best to determine the probability of tripping using MTC and the height of an obstacle [Best and Begg, 2007]. They developed a formula to quantify the probability of tripping (TPT(y)) over an obstacle of varying height (y).

$$TPT(y)=f\{PT(y),P_{MTC}(y),P_{VOB}(y)\} \quad \text{(Equation 1)}$$

$P_{MTC}(y)$ is the probability of a y cm obstacle occurring at MTC (P_{MTC} equals 1 when there is always a y cm obstacle) and $P_{VOB}(y)$ is the probability of seeing the y cm obstacle.

A separate study also utilized MTC to develop an autoregressive support vector machine to detect the risk of falling by elderly individuals. The system provided 95% detection accuracies for as little as 16 consecutive strides [Lai et al., 2008]. The significance of this study compared to others is that 16 consecutive strides is the fastest method that has been developed, while also accurately predicting the risk of falling.

1.2.2 Timed Up and Go

In 2011, Viccaro used timed up and go (TUG), the timed performance of a participant as he rises from a chair, walks 3 meters at his usual, preferred pace, turns around, returns to the chair and back to a seated position. Four hundred and fifty seven participants were followed over 1 year and each participant's TUG score was recorded. After one year, the participants' number of falls was correlated to the initial TUG score. Slow performers of the TUG test proved at greater risk of falls, when compared to the intermediate and faster performers of the TUG. Comparison between intermediate and fast performers did not

indicate greater risk of falling for either group. The study concluded that TUG could be used to screen older adults to determine if they are at high risk for falls [Viccaro et al., 2011].

1.2.3 Stepping Accuracy

Yamada, et al. (2011) hypothesized that stepping accuracy could be used as a predictive measure for the elderly at high risk for falls. The study included 118 elderly participants, each of which met 2 inclusion criteria.

1. A self- report of at least one fall within the past year
2. A TUG test time greater than 13.5 seconds

Each participant underwent a multi-target stepping task (MTST), which required him/her to walk on specific targets indicated on a black elastic mat, while ignoring other targets included as distractors. Any failure to step on the required target was categorized into a stepping failure (failure to step on the indicated target) or an avoidance failure (failure to avoid distractor targets). The results indicated that high risk fallers (already categorized by TUG) had significantly higher rate of avoidance failure and longer time to complete the MTST. However, no correlation could be found between the number of falls and number of avoidance failures [Yamada et al., 2011].

1.2.4 Arms and Trunk Contribution to Balance Recovery

Some tripping studies have focused on specific body segments and their contribution to balance recovery. If specific body segments can be isolated as critical to trip recovery, it will narrow the field of study aiding prediction of the risk of falls due to trips. Pijnappels led a study of ten healthy, young participants walking over-ground at their self-selected pace. After several control trials to acclimate the participant, an obstacle (15cm in height) would appear suddenly from the floor and trip the participant; the participant's kinematic responses were recorded. The experimental condition was then altered, and the participant was directed to clasp his arms behind his back. This experimental condition

was eventually thrown out, because the participants could not voluntarily keep their arms clasped behind their back while being tripped. To replace this data, a theoretical calculation was instead devised to predict the response if the arms were removed (a theoretical model, without arms). The study concluded that arms contribute a significant, functional role in balance recovery [Pijnappels, 2010]. This leads to the additional conclusion that arms could be critical to preventing a fall after a tripping event. However, due to the limitations of Pijnappels study, it would be ideal to revise the experimental protocol and perform a new study.

1.2.5 Local Stability

In 2000, Dingwell began to investigate the role of local stability in walking. Local stability is the sensitivity of the system to small, infinitesimal perturbations during walking. These perturbations are reflected in the natural stride to stride variations during walking (noise in the system). Local stability assumes the system is aperiodic and therefore the variations are measured in real time. One vector state space orbit will include one complete walking stride. The relationship between walking speeds and local stability in diabetic neuropathic patients was the research topic for the first local stability study [Dingwell, 2000]. For the study, 14 diabetic patients with significant peripheral neuropathy and 12 control subjects walked over-ground at self- selected pace while kinematic data was collected and then local stability was calculated. The method for calculating local stability, for all participants (neuropathic and control) is as follows:

A. The original time series is plotted and reviewed

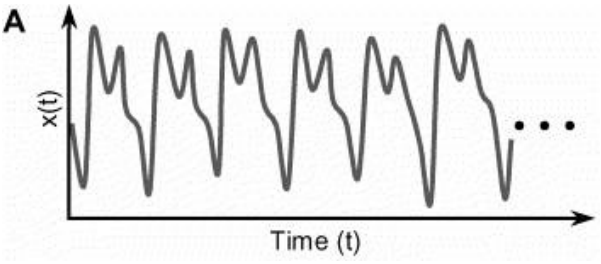

Figure 1. Original Time Series

B. The original time series and its time delayed copies are plotted to construct a vector state space. One complete orbit represents one walking stride.

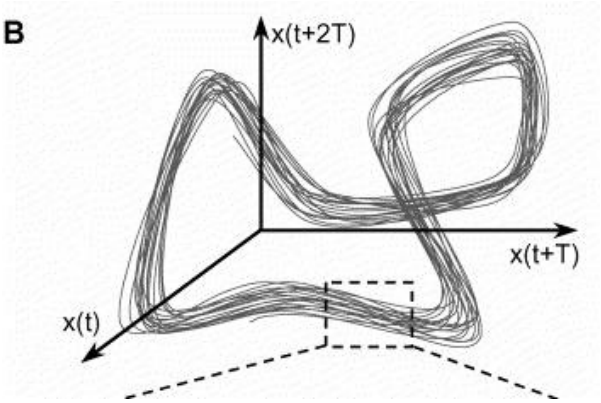

Figure 2. Vector State Space

C. Closer view indicates the divergence between neighboring trajectories resulting from local perturbations to the system.

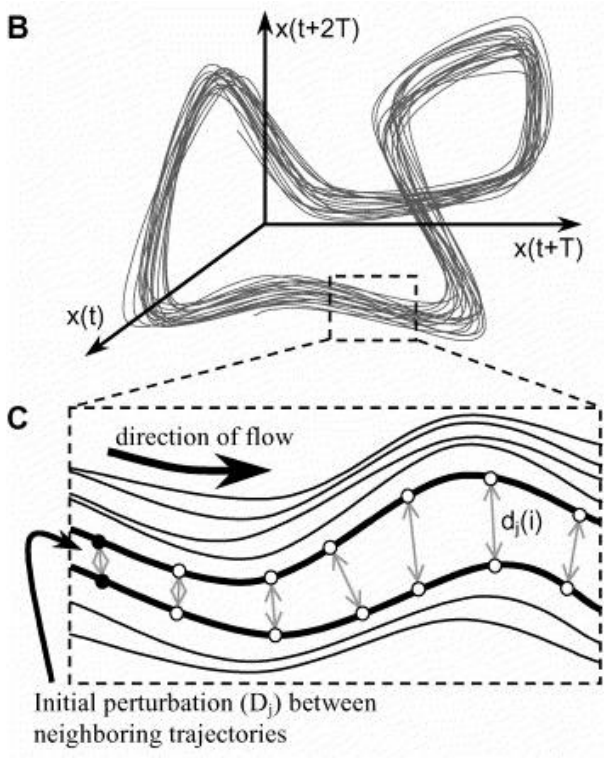

Figure 3. Vector State Space Divergence of Neighboring Trajectories

D. The average logarithmic divergence of neighboring trajectories is **λ** which is also the slope of the curve as indicated in Figure 4. **λ** is the local dynamic stability exponent.

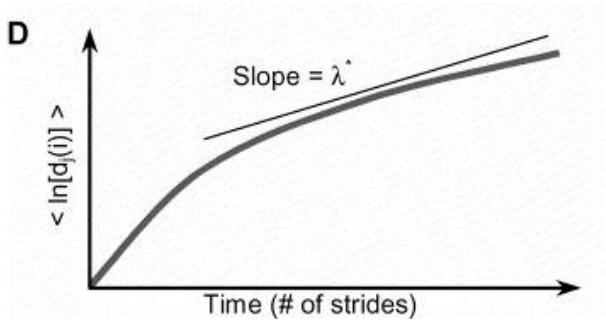

Figure 4. Average Logarithmic Divergence of Neighboring Trajectories

The results indicated that neuropathic patients had significantly lower **λ**, more local stability for all measures. Even without statistically significant differences between the

control and the neuropathic patients, strong predictive relationships were seen between local dynamic stability and walking speed [Dingwell et al., 2000].

Dingwell continued his study of local stability as a measure of walking gait by experimenting with local stability and kinematic variability of treadmill walking versus over-ground walking. The study had ten healthy young participants walk at a self-selected pace over-ground and then on a treadmill. The same methods used in his previous study (with neuropathic patients) were implemented to calculate local stability of each participant when walking over-ground and on the treadmill. The results indicated the subjects were more locally stable when walking on a treadmill versus over-ground. Since the results demonstrated increased local stability when walking on a treadmill, this must be a consideration when performing future treadmill experiments measuring stability. [Dingwell et al., 2001]

1.2.6 Orbital Stability

Once local stability was clearly defined, Dingwell began exploring whether a relationship between local stability and orbital stability exists. "Orbital stability is the tendency of the system's state to return to the periodic limit cycle orbit after small perturbations" [Dingwell and Kang, 2007]. Orbital stability will look at the variations between each period of the gait cycle (stride to stride fluctuations), while assuming that each stride is periodic (each stride being a constant fixed period). Orbital stability will only include one fixed point within the cycle (since periodicity is assumed), typically heel strike (x_k) and each subsequent heel strike (x_{k+1}). Each heel strike is compared to the mean of all heel strikes, indicated as the "fixed point" on the Poincare section in Figure 5. The difference between the mean heel strike and each individual heel strike is compared between each stride to measure the small perturbations growth or decay. Figure 5 graphically represents one heel strike (x_k), its subsequent heel strike (x_{k+1}) and the mean of all heel strikes (fixed point).

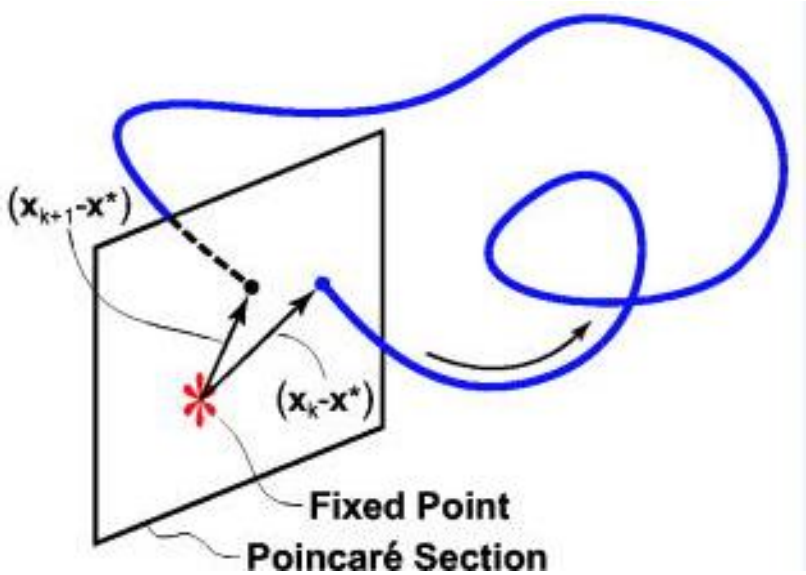

Figure 5. Poincare Section

Obtaining measurements from ten healthy young participants on a treadmill, Dingwell calculated the local and orbital stability for each participant. Each participant exhibited local instability while maintaining orbital stability in walking patterns. Dingwell also hypothesized that orbital stability would vary systematically across the gait cycle, however this hypothesis was not supported. While orbital stability did fluctuate, the fluctuations were small and did not follow a definable pattern [Dingwell and Kang, 2007].

1.2.7 Global Stability

Global stability is the ability of the system to accommodate finite perturbations, such as a slip or trip. In order to measure the ability of the system to accommodate finite perturbations, the system (the participant) must be subjected to a finite perturbation (tripped) and the response analyzed. Current research has measured responses to a trip, but the measures have not included calculation of global stability. Measures of global stability include; steps to recovery and time to recovery. Recovery was defined as the time at which the subject returned to his normal walking pattern.

My proposed next step in the current research is an experiment that causes a trip (finite perturbation) in order to measure global stability and attempt to correlate the global stability results to local stability. Orbital stability does not appear to be a good comparative measure for this study, since it lacks any significant fluctuations over the gait cycle. If any correlation is found to exist between local and global stability, local stability measures could eventually be used as predictive measures for global stability and assist with fall prediction.

1.3 Proposed Study

Previous experimentation involving defined tripping events have been conducted while overground walking. Either a rope was used, or a hidden obstacle appeared out of the ground to cause the trip [Pijnappels, 2010]. This method created the need for a large amount of subjects, as after one tripping event the subject was aware of the location of the obstacle. This proposed study included a tripping event while on a treadmill that could occur at any time the investigator chose.

Chapter Two: Methods

The creation of a controlled tripping event while on a treadmill presented a dilemma for the design of a new and unique tripping device.

2.1 Design of the Tripping Device

The original design began very generally, as a cuff that would attach to the subject's left ankle and originate from a rewind motor that paces with the subject. Initiation of a trip by the experimenter would engage the brake to stop forward motion of the left ankle. A strain gauge was used to continuously measure the tension in the cable that was attached to the ankle cuff. Although a simple theoretical design, the implementation became quite complex, including multiple components operated from National Instrument's Labview software. Pictures of the implemented tripping device are pictured and labeled in Figures 6, 7 & 8.

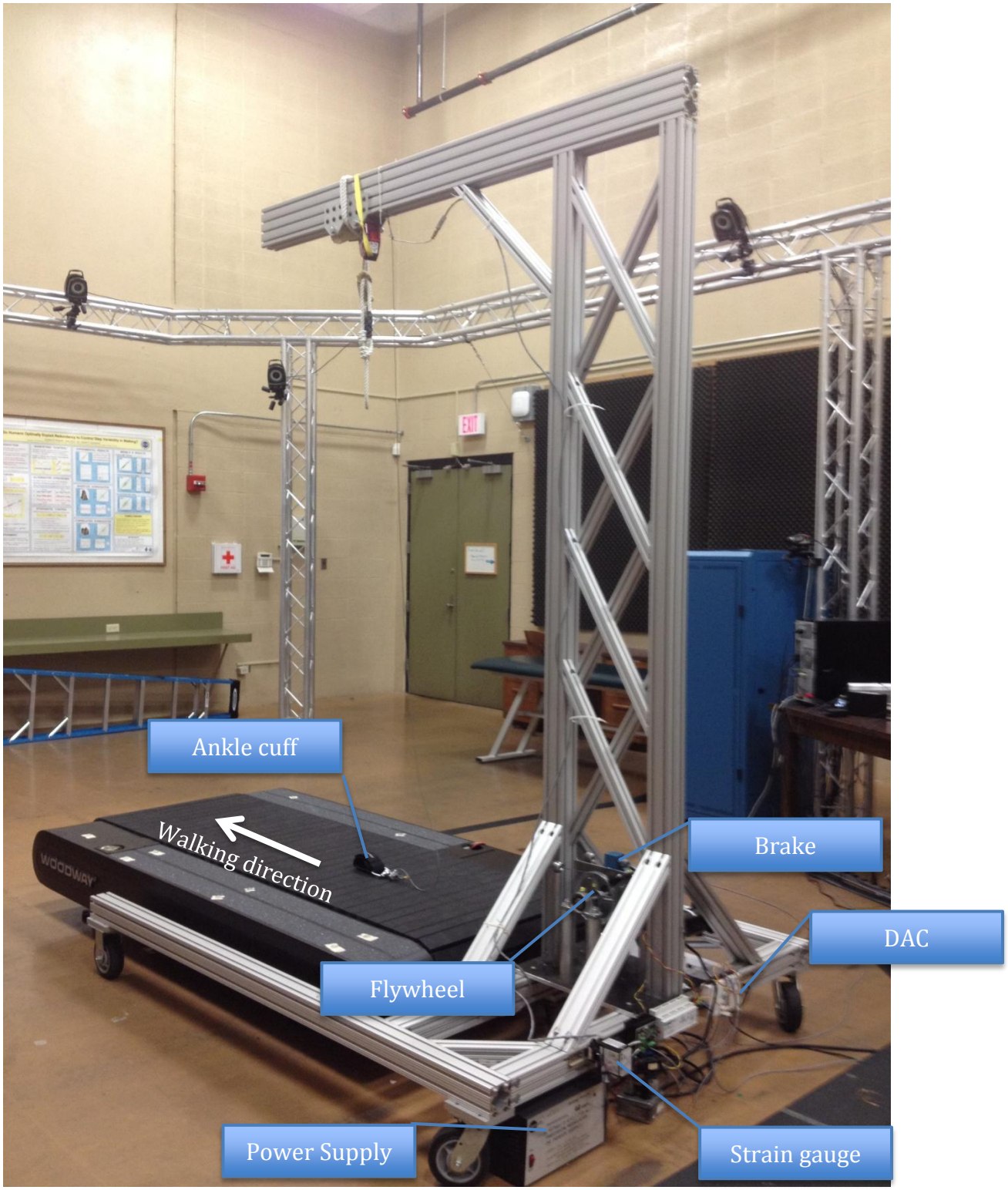

Figure 6. Treadmill with ankle cuff and tripping mechanism

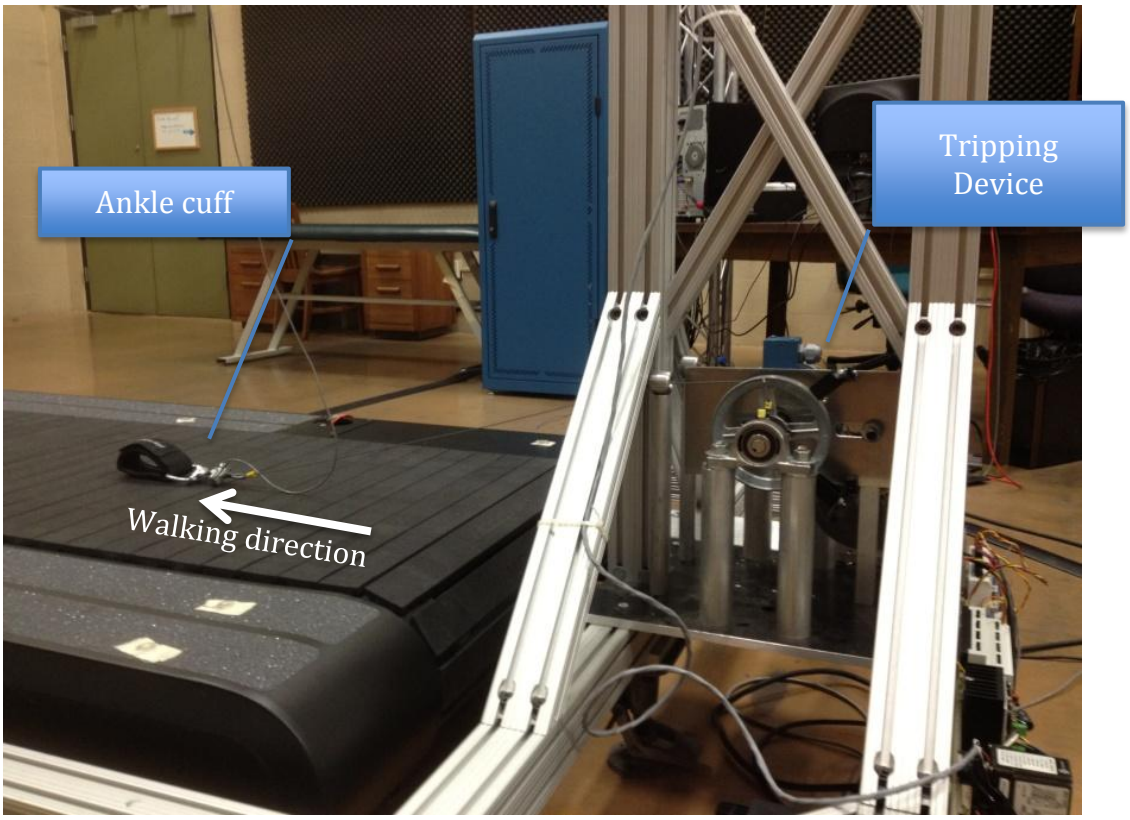

Figure 7. Treadmill with ankle cuff and tripping mechanism

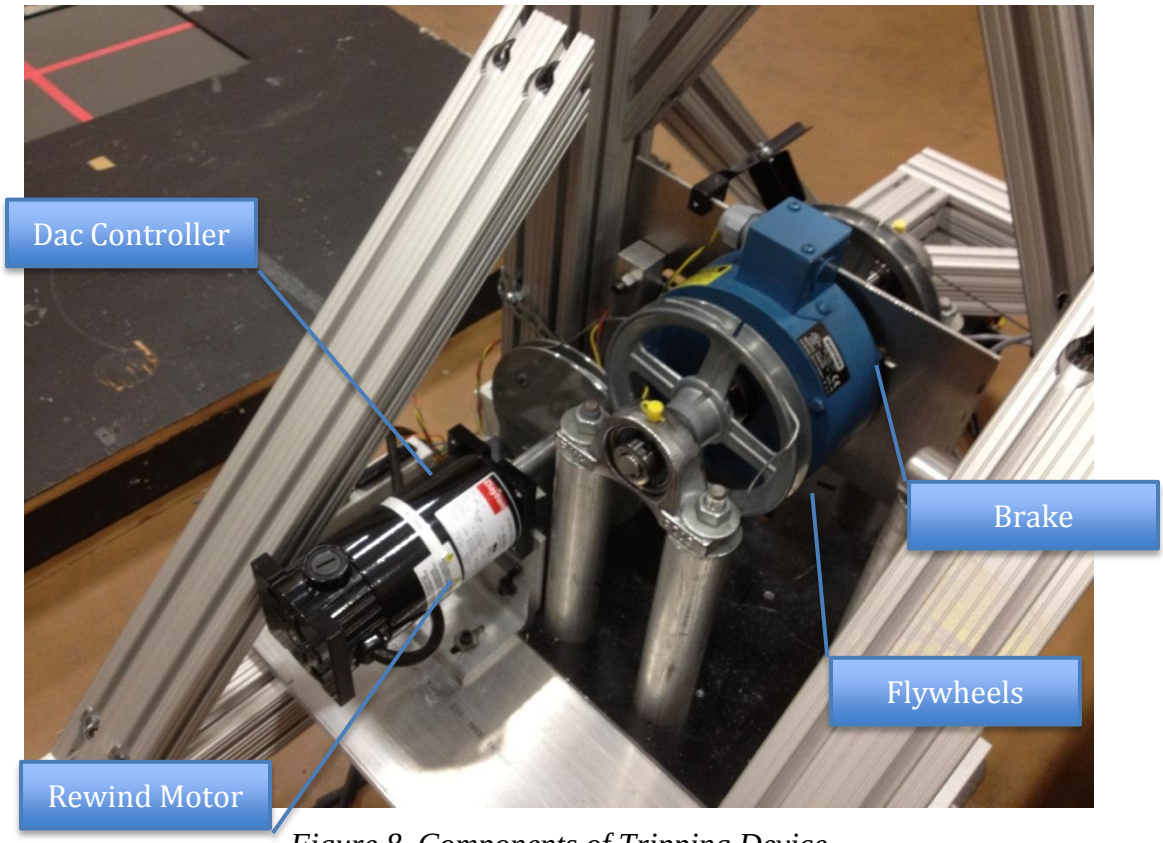

Figure 8. Components of Tripping Device

The specific components were as follows:

1. Rewind Motor and Rewind Motor Drive – Model 4Z143 from Grainger and model 1014-20-50 from Device Craft
2. Brake and Brake Power Supply – Model GBB90 and PS90 from Applied Industrial Technologies
3. USB DAC – USB-6211 from National Instruments
4. Power Supply – Model PR-401 from Tripp Lite
5. Strain Gauge and Strain Gauge Amplifier– Model MLP-50-T from Transducer Techniques and model AP4081 from PLC center #125423079

A specially designed program using National Instruments Labview software was used to control the gain on the rewind motor allowing the appropriate tension (adjustable via labview) to remain in the ankle cable, which prevented slack when in the stance phase of walking. The program allowed for a trip to be initiated at any point in the gait cycle, as

decided by the experimenter. The length of the trip was defined by the length of time the brake was engaged. This was coded into labview. The brake duration was set as 200 ms for this experiment. The strain gauge provided a continuous reading of the tension on the ankle cable, further ensuring an accurate capture of the time when the brake was activated and the subject was tripped. Although the trip signal was initiated from the software and controlled by the experimenter, did not occur at the same point in the gait cycle. The signal to trip was controlled entirely by the experimenter and the gait cycle phases were not directly measured during the experiment. However, the experimenter attempted to initiate the trip just after toe off of the left foot occurred.

Subjects were 18-35 years of age and healthy. Informed consent was required for each subject; the informed consent form is included as Appendix A. Once informed consent was received, the subject's height, weight, and leg length were measured and recorded along with a health/activity questionnaire**,** Appendix B. Each subject was prepared with 57 kinematic markers adhered to the skin with double sided tape. The markers are reflective and compatible with the Vicon MX camera system, the camera system used to collect all data for the experiment. In addition to physical kinematic markers, 20 digitized markers were included to be used for further analysis in Visual 3d. The location and description of the physical and digitized markers are included as Appendix C. In addition to kinematic markers, electromyography (EMG) was collected during the trial. Eight channels of EMG were collected, on four bilateral muscles. The muscles were the tibialis anterior, gastrocnemius, biceps femoris, and vastus lateralis. However, the data collected from the EMG electrodes were not analyzed as a part of this report.

The kinematic marker data were processed in Vicon Nexus to ensure continuous 3 dimensional coordinates for each marker. The data were exported from Vicon Nexus and imported into Visual 3D for further analysis. Within Visual 3D, the data sets were each time normalized to one gait cycle, using heel strike as the defining event. The gait cycle

was further subdivided to each right and left step for the entire timed trial, but only 120 steps were analyzed for each time trial.

2.2 Experimental Design

The experiment was designed as repeated measures, using 3 treadmill speeds (slow, preferred and fast) under 2 perturbation conditions (unperturbed and perturbed). The order of presentation of the different conditions was randomized between subjects to minimize the learning effect of repeated trials, figure 9. The tripping event during each perturbation trial was initiated at random times to prevent the subject from predicting the time of the trip. .

	Speed 1					Speed 2					Speed 3				
Subj	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
1	SN	SP	SN	SP	SN	MN	MN	MP	MN	MP	FN	FP	FN	FN	FP
2	MN	MP	MP	MN	MN	FN	FP	FN	FP	FN	SN	SN	SP	SN	SP
3	FN	FN	FN	FP	FP	SN	SP	SP	SN	SN	MN	MP	MN	MP	MN
4	SN	SN	SP	SP	SN	FN	FP	FP	FN	FN	MN	MP	MP	MN	MN
5	MN	MP	MN	MN	MP	SN	SN	SN	SP	SP	FN	FN	FP	FP	FN
6	FN	FN	FP	FN	FP	MN	MN	MP	MP	MN	SN	SN	SN	SP	SP
7	FN	FP	FN	FP	FN	MN	MP	MN	MN	MP	SN	SP	SN	SP	SN
8	MN	MN	MN	MP	MP	SN	SN	SP	SN	SP	FN	FP	FP	FN	FN
9	SN	SP	SP	SN	SN	FN	FN	FN	FP	FP	MN	MN	MP	MP	MN
10	FN	FN	FP	FP	FN	SN	SN	SP	SP	SN	MN	MN	MN	MP	MP
11	MN	MN	MN	MN	MP	FN	FP	FN	FN	FP	SN	SP	SN	SN	SP
12	SN	SP	SN	SN	SP	MN	MP	MN	MP	MN	FN	FN	FP	FN	FP
13	MN	MN	MN	MN	MP	FN	FP	FN	FN	FP	SN	SP	SN	SN	SP
14	FN	FN	FN	FP	FP	SN	SP	SP	SN	SN	MN	MP	MN	MP	MN
15	MN	MP	MN	MN	MP	SN	SN	SN	SP	SP	FN	FN	FP	FP	FN
16	MN	MN	MN	MP	MP	SN	SN	SP	SN	SP	FN	FP	FP	FN	FN
17	SN	SP	SN	SP	SN	MN	MN	MP	MN	MP	FN	FP	FN	FN	FP
18	FN	FN	FP	FN	FP	MN	MN	MP	MP	MN	SN	SN	SN	SP	SP
19	SN	SP	SN	SN	SP	MN	MP	MN	MP	MN	FN	FN	FP	FN	FP
20	SN	SN	SP	SP	SN	FN	FP	FP	FN	FN	MN	MP	MP	MN	MN

S = Slow *P = Perturbation*
M = Medium *N = No Perturbation*
F = Fast

Figure 9. Trial Randomization

The preferred walking speed was determined using the subject's leg length and the Froude calculation for preferred walking speed as defined by Hof and Vaughan. The Froude number utilized for preferred human walking speed is 0.40. [Hof, 1996 and Vaughan & O'Malley, 2005]

$$\mathbf{Fr} = \frac{v}{\sqrt{glo}} \qquad \textit{Equation 2}$$

With:

Fr = 0.40 = Froude number for preferred walking speed

v = velocity (m/s)

g = 9.81 m/s^2 = acceleration due to gravity

l_o = leg length of subject from greater trochanter to the floor (m)

The slow and fast speeds were 20% slower and 20% faster than the subject's preferred walking speed. The perturbation conditions included unperturbed and perturbed walking trials, however the cuff was attached during all trials. The unperturbed trials were designed as 5 min of total walking time for the subject, with 1 collection trial of 2 min recorded during the 5 min. The perturbation trials were also 5 min of continuous walking with 2 tripping events initiated at random times throughout the trial. The data recording time of the perturbation trials varied, but was approximately 2 min. The collection continued until the experimenter visually confirmed the subject's gait had returned to her normal pattern. The subject was not aware of when the trip would occur, nor was she aware when the trials were being collected. The subject was allowed rest breaks as needed throughout the experiment. After collection, the data were processed in the Vicon Nexus software and Visual 3D.

2.3 Hypotheses Tested

The kinematic data collected were analyzed to test the following hypotheses:

1. During unperturbed walking, healthy humans will exhibit lower variability when walking at slower speeds and greater variability at faster speeds.

2. When subjected to perturbations, healthy humans will exhibit faster kinematic recovery time when walking at slower speeds and slower kinematic recovery time at faster speeds.

Unfortunately during pilot testing of the experimental setup, the tripping device failed and was unable to be repaired. Two pilot subject's data had been collected and partially processed when a computer hard-drive failure also occurred and only one subject's data was recoverable. The data analysis for one subject was completed and included within the results of this report, but no statistical analysis was performed. The hypotheses were partially, but not fully, addressed. Due to the device failure variability is not addressed, but step time, step length, step width and steps to recovery were analyzed for the second hypothesis. This analysis can also be utilized to determine if the tripping device, as designed, produced a perturbation strong enough to elicit a significant trip and would be useful in future tripping/stability experiments.

Chapter Three: Results / Discussion

During normal walking, the subject increased step length as the speed increased, while the step width remained stable throughout speeds. As expected the average step time decreased as the walking speed increased, Table 1.

	Average Step Length (m)	Average Step Width (m)	Average Step Time (s)
Slow Speed	0.57 ± 0.01	0.13 ± 0.01	0.60 ± 0.01
Preferred Speed	0.64 ± 0.01	0.13 ± 0.01	0.55 ± 0.01
Fast Speed	0.71 ± 0.003	0.13 ± 0.003	0.51 ± 0.002

Table 1. Unperturbed Walking Average Step Length, Step Width and Step Time

The right step length and left step length were analyzed separately during normal walking in order to determine the effect, if any, of the cuff on the step lengths, Table 2.

	Average Right Step Length (m)	Average Left Step Length (m)
Slow Speed	0.58 ± 0.02	0.56 ± 0.02
Preferred Speed	0.66 ± 0.01	0.63 ± 0.01
Fast Speed	0.71 ± 0.02	0.70 ± 0.02

Table 2. Unperturbed Walking Average Step Length of Right and Left Steps

Table 2 indicates the left step length (cuff attached to the left ankle) was shorter for all speed conditions, however the difference appears minimal. It should be considered for future experimentation, to compare the subject walking at each speed with and without the cuff to verify there is no significant difference.

A faster step time and longer step length during faster walking imply that when tripped the steps to recovery should increase and time to recovery should be longer. Recovery was determined by a return of step length within range of the step lengths during normal walking. The slow speed, 20% slower than preferred, generally required 4 steps and 2.4s to recover once tripped, Figure 10.

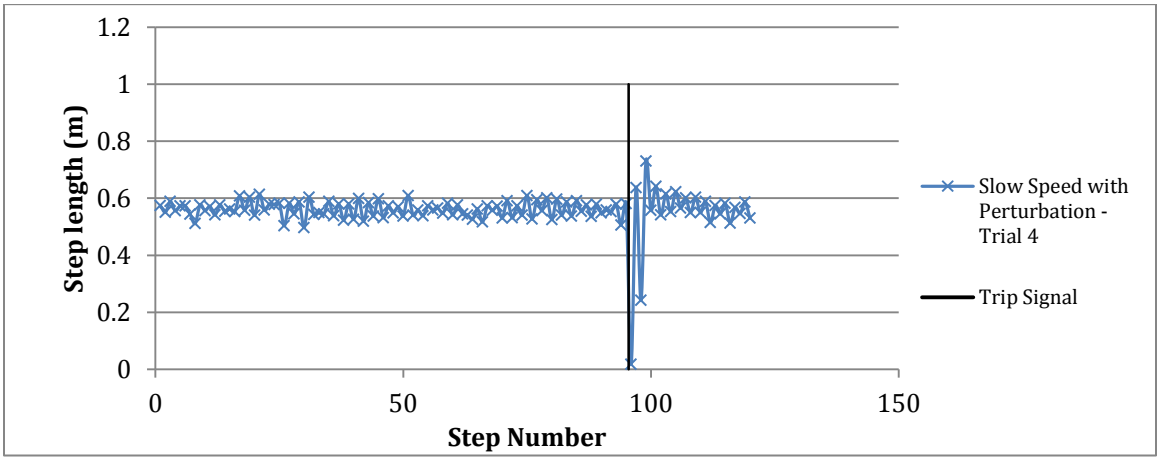

Figure 10. Perturbed Walking Step Number vs Step Length for Slow Walking

When walking at preferred speed the steps to recover increased to 6 steps and required 3.3s, Figure 11.

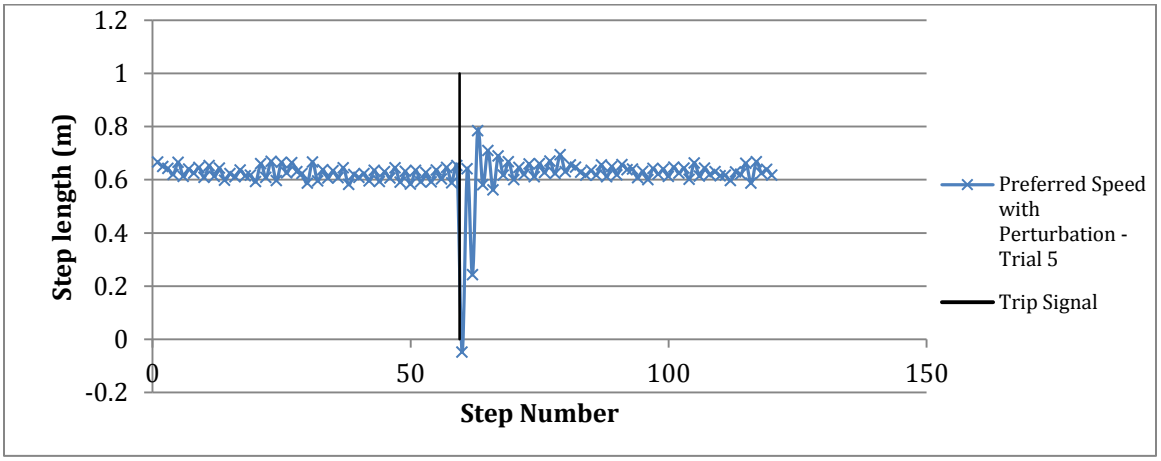

Figure 11. Perturbed Walking Step Number vs Step Length for Preferred Walking

Fast walking, 20% above preferred, generally required 8 steps and 4.1s in order to recover from the trip, Figure 12.

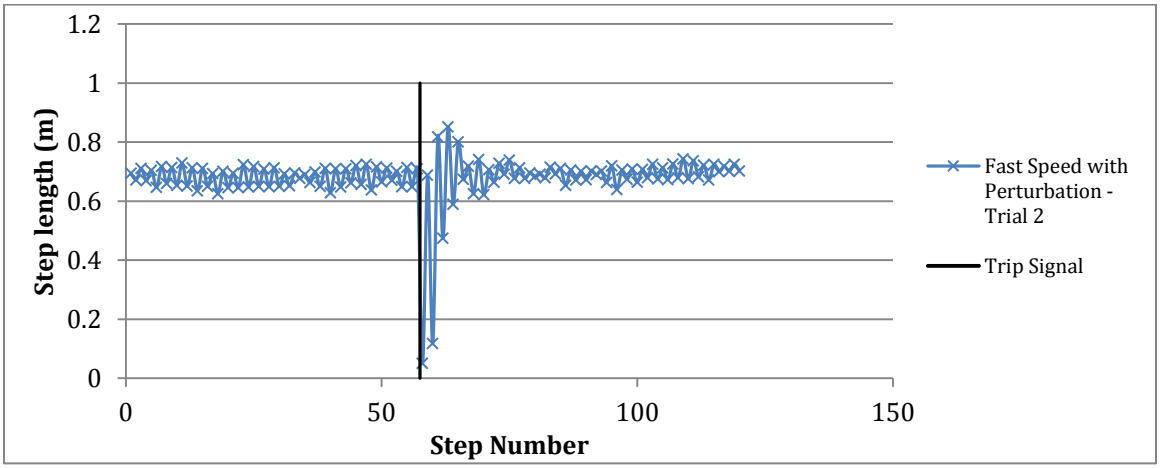

Figure 12. Perturbed Walking Step Number vs Step Length for Fast Walking

The increasing speed condition increased the number of steps to recovery and although faster speeds also had faster steps times, the overall time to recovery was longer with faster speed due to the increased number of steps required.

Consistent across all speed conditions is a very short initial step immediately following the trip. According to Eng (1994) when tripped during early swing phase subjects responded with an elevating strategy that increased the step length immediately following the trip. When tripped during late swing phase the subject responded with a lowering strategy that decreased the step length immediately following the trip. This is counterintuitive, as the step length should increase in an attempt to move the base of support beneath the center of mass that continued to move forward since the trip for this study was initiated in early swing. This short step could be a result of treadmill walking, but more likely is a side effect of the device design. While the brake is activated for a very short time (200 ms), the release actually felt at the ankle was not that fast. So, it is possible the ankle is held longer than a naturally occurring trip, forcing the initial short step. Following the initial short step, for each speed condition, the second step was within

range of the normal average step length. This would require further analysis to determine if this is typical across subjects, or unique to this particular subject. The third recovery step was always another shorter step, followed by a fourth longer step. After 4 steps, the slow speed step lengths were normalized again, while the preferred and faster speeds experienced more short to long step oscillations before returning to normal.

Chapter Four: Conclusion

As expected, increasing walking speed, was correlated with an increase in step length and faster step times. This leads to more steps for recovery and a longer recovery time when tripped at faster speeds. Previous studies have not varied walking speed to determine if a correlation exists. Given the high risk fall population are elderly individuals who tend to walk slower, it is necessary to determine if a correlation exists. Due to technical issues with the tripping device and computer hardware, only one subject was analyzed. Therefore, no formal determination regarding the hypotheses presented was determined, although the one subject's data appears to confirm the second hypothesis. However, this experiment confirmed that the tripping device, as designed, can initiate a significant and measurable tripping event. The device, if repaired, has the potential to be used to classify the recovery strategies used by young healthy participants when subjected to a perturbation at varying speeds.

Appendix A: IRB Approval and Consent Form

OFFICE OF RESEARCH SUPPORT

THE UNIVERSITY OF TEXAS AT AUSTIN

P.O. Box 7426, Austin, Texas 78713 · Mail Code A3200
(512) 471-8871 · FAX (512) 471-8873

FWA # 00002030

Date: 11/14/11

PI: Jonathan B Dingwell

Dept: Kinesiology and Health Educati

Title: Dynamic Stability During Perturbed Human Walking

Re: IRB Expedited Approval for Protocol Number 2011-09-0025

Dear Jonathan B Dingwell:

In accordance with the Federal Regulations the Institutional Review Board (IRB) reviewed the above referenced research study and found it met the requirements for approval under the Expedited category noted below for the following period of time: 11/14/2011 to 11/13/2012 . *Expires 12 a.m. [midnight] of this date.*

Expedited category of approval:

☐ 1) Clinical studies of drugs and medical devices only when condition (a) or (b) is met. (a) Research on drugs for which an investigational new drug application (21 CFR Part 312) is not required. (Note: Research on marketed drugs that significantly increases the risks or decreases the acceptability of the risks associated with the use of the product is not eligible for expedited review.)
(b) Research on medical devices for which (i) an investigational device exemption application (21 CFR Part 812) is not required; or (ii) the medical device is cleared/approved for marketing and the medical device is being used in accordance with its cleared/approved labeling.

☐ 2) Collection of blood samples by finger stick, heel stick, ear stick, or venipuncture as follows: (a) from healthy, non-pregnant adults who weigh at least 110 pounds. For these subjects, the amounts drawn may not exceed 550 ml in an 8 week period and collection may not occur more frequently than 2 times per week; or (b) from other adults and children, considering the age, weight, and health of the subjects, the collection procedure, the amount of blood to be collected, and the frequency with which it will be collected. For these subjects, the amount drawn may not exceed the lesser of 50 ml or 3 ml per kg in an 8 week period and collection may not occur more frequently than 2 times per week.

☐ 3) Prospective collection of biological specimens for research purposes by non-invasive means. Examples:
(a) Hair and nail clippings in a non-disfiguring manner.
(b) Deciduous teeth at time of exfoliation or if routine patient care indicates a need for extraction.
(c) Permanent teeth if routine patient care indicates a need for extraction.
(d) Excreta and external secretions (including sweat).

(e) Uncannulated saliva collected either in an un-stimulated fashion or stimulated by chewing gumbase or wax or by applying a dilute citric solution to the tongue.
(f) Placenta removed at delivery.
(g) Amniotic fluid obtained at the time of rupture of the membrane prior to or during labor.
(h) Supra- and subgingival dental plaque and calculus, provided the collection procedure is not more invasive than routine prophylactic scaling of the teeth and the process is accomplished in accordance with accepted prophylactic techniques.
(i) Mucosal and skin cells collected by buccal scraping or swab, skin swab, or mouth washings.
(j) Sputum collected after saline mist nebulization.

☒ 4) Collection of data through non-invasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications).
Examples:
(a) Physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject's privacy.
(b) Weighing or testing sensory acuity.
(c) Magnetic resonance imaging.
(d) Electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography.
(e) Moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual.

☐ 5) Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for non-research purposes (such as medical treatment or diagnosis).
Note: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.

☒ 6) Collection of data from voice, video, digital, or image recordings made for research purposes.

☒ 7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.
Note: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.

☒ Use the attached approved informed consent document(s).

☐ You have been granted a Waiver of Documentation of Consent according to 45 CFR 46.117 and/or 21 CFR 56.109(c)(1).

☐ You have been granted a Waiver of Informed Consent according to 45 CFR 46.116(d).

Responsibilities of the Principal Investigator:

1. Report immediately to the IRB any unanticipated problems.

2. Submit for review and approval by the IRB all modifications to the protocol or consent form(s). Ensure the proposed changes in the approved research are not applied without prior IRB review and approval, except when necessary to eliminate apparent immediate hazards to the subject. Changes in approved research implemented without IRB review and approval initiated to eliminate apparent immediate hazards to the subject must be promptly reported to the IRB, and will be reviewed under the unanticipated problems policy to determine whether the change was consistent with ensuring the subjects continued welfare.

3. Report any significant findings that become known in the course of the research that might affect the willingness of subjects to continue to participate.

4. Ensure that only persons formally approved by the IRB enroll subjects.

5. Use only a currently approved consent form, if applicable.
   Note: Approval periods are for 12 months or less.

6. Protect the confidentiality of all persons and personally identifiable data, and train your staff and collaborators on policies and procedures for ensuring the privacy and confidentiality of subjects and their information.

7. Submit a Continuing Review Application for continuing review by the IRB. Federal regulations require IRB review of on-going projects no less than once a year a reminder letter will be sent to you two months before your expiration date. If a reminder is not received from Office of Research Support (ORS) about your upcoming continuing review, it is still the primary responsibility of the Principal Investigator not to conduct research activities on or after the expiration date. The Continuing Review Application must be submitted, reviewed and approved, before the expiration date.

8. Upon completion of the research study, a Closure Report must be submitted to the ORS.

9. Include the IRB study number on all future correspondence relating to this protocol.

If you have any questions contact the ORS by phone at (512) 471-8871 or via e-mail at orsc@uts.cc.utexas.edu.

Sincerely,

James P. Wilson

James Wilson, Ph.D.
Institutional Review Board Chair

APPROVED BY IRB ON: 11/14/2011 EXPIRES ON: 11/13/2012
IRB # 2011-09-0025

Informed Consent to Participate in Research
The University of Texas at Austin

You are being asked to participate in a research study. This form provides you with information about the study. The Principal Investigator (the person in charge of this research) or his/her representative will provide you with a copy of this form to keep for your reference, and will also describe this study to you and answer all of your questions. Please read the information below and ask questions about anything you don't understand before deciding whether or not to take part. Your participation is entirely voluntary and you can refuse to participate without penalty or loss of benefits to which you are otherwise entitled.

Title of Research Study:

"Dynamic Stability During Perturbed Human Walking"

Investigator(s):

Jonathan B. Dingwell, Ph.D. – *Principle Investigator*
Department of Kinesiology & Health Education
University of Texas at Austin
1 University Station, D3700
Bellmont Hall, Rm. 536
Phone: (512) 232-1782
E-Mail: jdingwell@mail.utexas.edu

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Funding Sources:
The National Institutes of Health:
National Institute of Biomedical Imaging & Bioengineering
http://www.nibib.nih.gov/
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National Institute of Child Health & Human Development
http://www.nichd.nih.gov/
Grant # 1-R01-HD059844

What is the purpose of this study?

The purpose of this study is to determine how people respond to various physical perturbations encountered during human walking. Physical perturbations are defined as a disruption to normal walking, such as what might occur when you slip or trip over an object. For this experiment, perturbations will be administered via a cable attached to your ankle. Gait parameters after the perturbation will be compared to the same parameters before perturbation to gain an understanding of perturbation effects. Your normal walking patterns as well as your responses to these perturbations will be tested at various walking speeds. By understanding how perturbations effect walking, we can better develop interventions and treatments to prevent falls that occur during walking.

Subjects participating in this study will consist of approximately 20 healthy volunteers between the ages of 18 and 35. These will be subjects who have no history of physical or neurological problems that might affect their ability to walk on a treadmill.

What will be done if you take part in this research study?

Testing will consist of the following procedures to be completed during a single experimental session:

- You will be asked to report to the Nonlinear Biodynamics Laboratory at the University of Texas at Austin, located in Bellmont Hall, Room 530. Wear comfortable shorts and shoes appropriate for extensive walking. Bring a sleeveless shirt, preferably a tank top. Gentlemen may be asked to perform shirtless.
- Before being admitted to the study, you will be screened for your suitability to participate by completing a brief Health History Questionnaire. You will also be asked about your typical weekly exercise habits.
- If you qualify to participate in the study, we will measure your height and weight, as well as the lengths of various individual body segments, including thigh, lower leg, and foot lengths, hip width, etc. These measurements do not hurt or feel uncomfortable.
- To become acclimated to the motorized treadmill, you will be asked to walk across a range of speeds, including speeds that are somewhat faster and somewhat slower than your comfortable walking speeds for 15-minutes. We will use these trials to determine your own personal "preferred" walking speed.
- Next, you will be asked to wear different measuring devices. These will include small reflective markers attached to various points on your body to record the movements of your body segments and several small electrodes that will be attached to the surface of your skin to measure the electrical activity of your muscles during these movements. These markers and electrodes will be attached with double-sided tape. The areas of skin where the electrodes will be placed will first be shaved and wiped clean with alcohol.
- You will then be asked to complete a series of 30-35 walking trials. Each trial will last 3 minutes. For each trial, the treadmill speed will be set to either your preferred speed, somewhat faster, or somewhat slower than your preferred speed. Each speed will remain constant for each 3 minute walking trial.
- During some trials, you may experience moderate perturbations. These perturbations will be applied by lightweight cables attached to your ankle. The magnitudes of these perturbations will be set so that you might stumble for a few steps before you can continue walking comfortably, but they should not be so large as to cause you to actually fall.
- You will be allowed at least 2 minutes, or as much time as you need, to rest between trials.
- You can stop the warm-up or any of the trials at any point and for any reason.

The Project Duration is:

Participation will involve a single experimental sessions, lasting approximately 3½ hours in duration.

What are the possible discomforts and risks?

The above procedures are not expected to be painful or uncomfortable in a healthy individual, save for some minor discomfort that may be experienced during the maximum strength testing. If you do find any of the procedures to be prohibitively uncomfortable, you should immediately tell the investigator and they will be discontinued. None of the devices being used in this study are invasive.

- As during any moderate exercise, there is a risk of heart attack or stroke. This risk will be minimized by asking you to complete the Health History Questionnaire to ensure that you are physically active and that you do not have any illnesses or injuries, or are taking any medications that might indicate that you would be at undue risk of experiencing a heart attack or stroke.

- Again, as during any moderate exercise, while completing the muscle strength testing or while walking on the treadmill there is a risk that you could experience a muscular injury, such as a muscle strain. Also, it is possible that muscle soreness may develop 24 to 48 hours after testing. To help reduce these risks, a warm-up and stretching session will be mandatory prior to performing these tests, and you will be allowed as much time as you need to rest between trials to minimize the effects of fatigue.
- During the walking trials, there is a possible risk of injury from stepping up onto or down off of the treadmill that is elevated approximately 12 inches above the floor. There is also a risk that you could trip or fall while walking, particularly during the perturbation trials. To reduce these risks, you will be asked to wear a safety harness that will catch you in the event of a fall while not constricting your movements.
- Additionally, the treadmill that will be used is equipped with an emergency "STOP" button that the investigator conducting the experiment will control. In the event of any unwanted event, the investigator will press this button to stop the treadmill immediately.
- During the walking trials, there is a risk that you may become overexerted and tired. To reduce this risk, you will not be asked to perform any tasks that are beyond the scope of what you might do during your normal daily activities or during moderate exercise. Additionally, you will be allowed to rest as long as you need between trials, and you may stop at any time if you feel the need.
- Some slight discomfort may also be experienced during removal of the reflective markers, similar to removing a band-aid. If you experience skin irritation, this should subside on its own by the following day.
- There may also be additional risks that are unknown at this time. If you wish to discuss the information above or any other risks you may experience, you may ask questions now or contact the Principal Investigators listed on the front page of this form at any time.

What are the possible benefits to you or to others?

There are no direct benefits to you by participating in this study.

This study is part of a series of experiments being conducted by the University of Texas Nonlinear Biodynamics Lab to investigate the variability and dynamic stability of human walking. We hope that these studies will contribute to a better understanding of the mechanisms humans use to maintain stability and to prevent falls.

If you choose to take part in this study, will it cost you anything?

No. Your participation is completely voluntary and free of charge.

Will you receive compensation for your participation in this study?

You will be compensated for your time in the amount of $40 for completing this experiment. If you anticipate that payments for *all* research and survey compensation received from UT Austin to collectively total $450.00 or more for the calendar year, you will also be asked to provide your social security number.

Disclosure of your social security number (SSN) is requested from you in order for The University of Texas at to process compensation for research activities and to pay you if the total compensation from UT Austin amounts to $450 or more. No statute or other authority requires that you disclose your SSN for that purpose. Failure to provide your SSN, however, may result in no payment or compensation for participation beyond $449 for that fiscal year. Further disclosure of your SSN is governed by the Public Information Act (Chapter 552 of the Texas Government Code) and other applicable law.

What if you are injured because of the study?

By participating in this study, there is a small chance of being injured, as discussed above. There are no plans for payment or compensation in the event of a research-related injury. However, if you are a University of Texas

student, you may receive medical attention for injuries from the Student Health Center in the same manner as other students.

If you do not want to take part in this study, what other options are available to you?

Your participation in this study is entirely voluntary. You are free to refuse to be in the study, and your refusal will not influence current or future relationships with The University of Texas at Austin (and or participating sites such as AISD or any other organization).

How can you withdraw from this research study and who should you call if you have questions?

If you wish to stop your participation in this research study for any reason, you should contact the principal investigator: Dr. Jonathan Dingwell at 512-232-1782 (or email: jdingwell@mail.utexas.edu). You should also call the principal investigator for any questions, concerns, or complaints about the research. You are free to withdraw your consent and stop participation in this research study at any time without penalty or loss of benefits for which you may be entitled. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

In addition, if you have questions about your rights as a research participant, or if you have complaints, concerns, or questions about the research, please contact the Office of Research Support at (512) 471-8871.

How will your privacy and the confidentiality of your research records be protected?

Each subject will be assigned a unique *Subject ID* code, which will *only* be identified with their name on the Subject Contact Information Form. The Health History Questionnaire will not contain any personally identifying information. If a potential subject is found to be ineligible to participate because they fail to meet inclusion criteria, all of their screening data and any other identifiable information will be destroyed. These two forms and this Informed Consent Form will be stored in a locked file cabinet inside a locked office. In all other cases, electronic data will only be identifiable by your unique *Subject ID* code. Only the director of the project (Dr. Dingwell) will have access to a master list that will link your identity to your code. The electronic data will be stored on DVD media and also kept in a locked file cabinet in Dr. Dingwell's office. These data will only contain fully de-identified, non-sensitive information and will be maintained indefinitely.

The records of this study will be stored securely and kept confidential. Authorized persons from The University of Texas at Austin and members of the University of Texas Institutional Review Board, have the legal right to review your research records and will protect the confidentiality of those records to the extent permitted by law. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study. Because this research project is sponsored (i.e., receives funding from outside UT-Austin) then the National Institutes of Health will also have the legal right to review your research records.

If in the unlikely event it becomes necessary for the Institutional Review Board to review your research records, then the University of Texas at Austin will protect the confidentiality of those records to the extent permitted by law. Your research records will not be released without your consent unless required by law or a court order. The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate you with it, or with your participation in any study. If the results of this research are published or presented at scientific meetings, your identity will not be disclosed.

Will the researchers benefit from your participation in this study?

The researchers will gain no benefit from your participation in this study beyond the publication and/or presentation of the results obtained from the study.

Signatures:

As a representative of this study, I have explained the purpose, the procedures, the benefits, and the risks that are involved in this research study:

Signature and printed name of person obtaining consent — Date

You have been informed about this study's purpose, procedures, possible benefits and risks, and you have received a copy of this Form. You have been given the opportunity to ask questions before you sign, and you have been told that you can ask other questions at any time. You voluntarily agree to participate in this study. By signing this form, you are not waiving any of your legal rights.

Printed Name of Subject — Date

Signature of Subject — Date

Signature of Principal Investigator — Date

Photograph / Videotape Consent:

As a part of your participation as a volunteer in this scientific research investigation, you may be photographed or videotaped during the course of this experiment. Any photographs and/or videotapes of your performance (without your name or likeliness revealed) may be shown to educational audiences, such as conferences. Your consent to be photographed or videotaped is independent of your consent to participate in this investigation. If you have any questions about this consent, you can contact Jonathan Dingwell at (512) 232-1782. By signing below, you hereby give permission for any photographs or videotapes made during the course of this research study to be also used for educational purposes.

Signature of Subject — Date

Signature of Principal Investigator — Date

You will be given a copy of this information to keep for your records.

Appendix B: Other Forms

HEALTH HISTORY QUESTIONNAIRE

"Dynamic Stability During Perturbed Human Walking"

IRB # 2011-09-0025 ***Subject ID:*** _____

Date of Birth (mm/dd/yy): _____ Age: _____

MALE: _____ FEMALE: _____

Height: _____ ft./in. = _____ in. × 0.0254 = _____ m

Weight: _____ lbs. × 0.4567 = _____ kg.

BMI (kg/m^2): _____ (BMI > 35 excludes)

1. Are you taking any medications on a regular basis?
   Y / N
   (Exclusions include: Psychotropics, Antihistamines, Asthma Meds, Aldomet, Clonidine, Anti-Depressants, Anti-Anxiety Meds)
2. Any over- the -counter meds?
   Y / N
   If yes, explain:
3. Do you have any disability or impairment that affects you when you walk?
   Y / N
   (If yes, excludes.)

4. Have you had any broken bones, surgery, or injury to lower extremities?

   Y / N

   If yes, explain:

5. Do you have arthritis? Does it cause pain or discomfort when you stand or walk?

   Y / N

   If yes to discomfort, excludes.

6. Have you had any significant medical problems within the last 10 years?

   Y / N

   If yes, explain:

7. Do you have a history of neurological diseases likely to affect your ability to stand or walk, including CVA (stroke), disc disease, peripheral neuropathy, or lower extremity weakness? Y / N

   If yes, exclude.

8. Do you have any history of back problems, such as low back pain?

   Y / N

   If yes, explain.

9. Do you have any problems with standing balance?

   Y / N

   If yes, excludes.

10. Do you have any drug and/or alcohol dependence?

    Y / N

    If yes, excludes.

11. Do you have any significant visual impairments?

    Y / N

    Examples: loss of binocular vision or the presence of double vision

    If yes, excludes.

12. Do you have any heart problems or coronary artery disease?

Y / N

If yes, excludes.

13. Do you have hypertension?

Y / N

If yes, excludes.

15. Do you have any lung or respiratory problems?

Y / N

If yes, excludes.

16. Do you smoke?

Y / N

Pattern?

17. Do you use alcohol?

Y / N

Pattern?

18. Do you use caffeine (cola, coffee, etc.)?

Y / N

Pattern?

19. Do you have any allergies that require medication?

Y / N

If yes, explain.

20. Have you fallen during the past year?

Y / N

If yes, explain how the fall occurred and what injuries (if any) resulted.

Please complete Physical Activity Information on the following page

Physical Activity: Please fill out the following three sections: **Work, Sport, and Leisure**

Work Section:

Question	**Response**	**Points**
What is your main occupation?	low activity	1
	moderate activity	3
	high activity	5
At work I sit	never	1
	seldom	2
	sometimes	3
	often	4
	always	5
At work I stand	never	1
	seldom	2
	sometimes	3
	often	4
	always	5
At work I walk	never	1
	seldom	2
	sometimes	3

	often	4
	always	5
At work I lift heavy loads	never	1
	seldom	2
	sometimes	3
	often	4
	always	5
After working I am tired	very often	5
	often	4
	sometimes	3
	seldom	2
	never	1
At work I sweat	very often	5
	often	4
	sometimes	3
	seldom	2
	never	1

In comparison of others of my own age I think my work is physically	much heavier	5
	heavier	4
	as heavy	3
	lighter	2
	much lighter	1

Sport Section:

Question	**Response**	**Points**
Do you play sports?	Yes then continue to Sport Part I.	-
	No then continue on to "Leisure Section"	-

Sport Part I.

Question	Response	Points
In comparison with others of my own age I think my physical activity during leisure time is	much more	5
	More	4
	the same	3
	Less	2
	much less	1
During leisure time I sweat	very often	5
	Often	4
	sometimes	3
	Seldom	2
	Never	1
During leisure time I play sport	Never	1
	Seldom	2
	sometimes	3
	Often	4

	very often	5

Sport Part II.

Question	**Response**	**Points**
What sport do you play most frequently	low intensity	0.76
	medium intensity	1.26
	high intensity	1.76
How many hours do you play a week?	< 1 hour	0.5
	1-2 hours	1.5
	2-3 hours	2.5
	3-4 hours	3.5
	> 4 hours	4.5
How many months do you play in a year?	< 1 month	0.04
	1-3 months	0.17
	4-6 months	0.42
	7-9 months	0.67
	> 9 months	0.92

Leisure Section:

Question	Response	Points
During leisure time I watch television	never	1
	seldom	2
	sometimes	3
	often	4
	very often	5
During leisure time I walk	never	1
	seldom	2
	sometimes	3
	often	4
	very often	5
During leisure time I cycle	never	1
	seldom	2
	sometimes	3
	often	4
	very often	5

How many minutes do you walk and/or cycle per day to and from work school and shopping?	< 5 minutes	1
	5-15 minutes	2
	15-30 minutes	3
	30-45 minutes	4
	> 45 minutes	5

Final Total Score: _____

(To be completed by researcher)

SUBJECT INFORMATION FORM

"Dynamic Stability During Perturbed Human Walking"

IRB # 2011-09-0025 ***Subject ID:***

NOTE: FILLING OUT THIS FORM IS COMPLETELY OPTIONAL

We request this information in case you may be interested in being contacted in the future regarding the outcomes of this study and/or possible participation in future studies. Completing this form is not required.

This form and this information will be kept strictly confidential.

Name: _____

Postal Address: _____

_____

_____

Telephone Number: (_____) _____

E-Mail Address: _____

This study is being funded by a grant from the National Institutes of Health (NIH). NIH requires researchers to report gender, race, and ethnicity data for all NIH funded studies.

Your name and personal information will not be reported with this data. This part of the form is completely optional, not completing it will not affect your participation in this study in any way.

Gender: ☐ Male ☐ Female ☐ Not Reporting

Race: ☐ American Indian/Alaska Native ☐ Asian ☐ Native Hawaiian/Pacific Islander

☐ Black or African American ☐ White ☐ More than one race

☐ Unknown or Not Reporting

Ethnicity: ☐ Hispanic or Latino ☐ Not Hispanic or Latino

☐ Unknown or Not Reporting

SUBJECT DATA FORM

"Dynamic Stability During Perturbed Human Walking"

IRB # 2011-09-0025 ***Subject ID:***

_____

Date: _____

Body Weight _____ kg Height _____m

Age ____yr Gender: M/F leg length _____

Dominant Leg (Right / Left)

Physical Activity Score _____

Preferred Walking Speed

From Familiarization testing:

1) fast: _____ pref: _____slow: _____
2) fast: _____ pref: _____slow: _____
3) fast: _____ pref: _____slow: _____

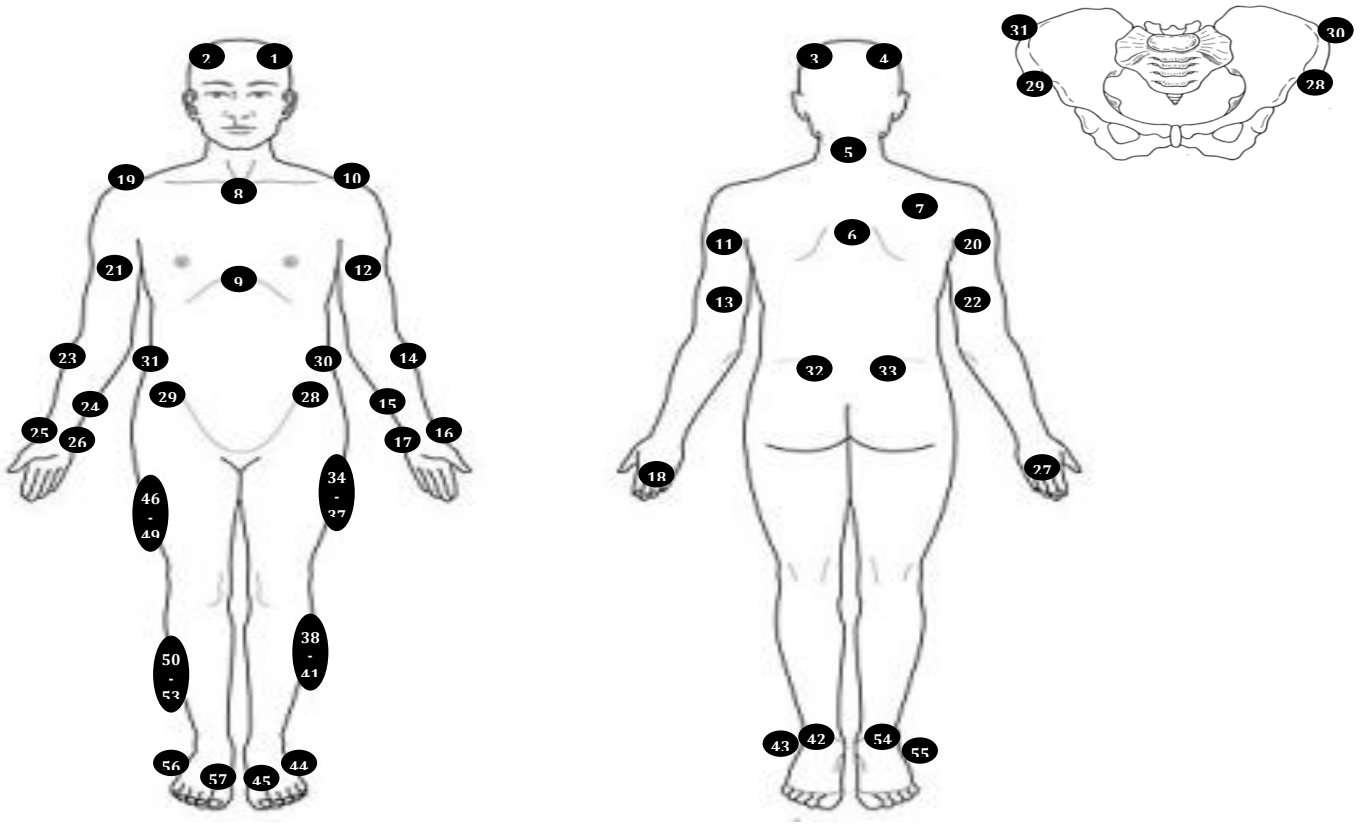
Pref_Avg_____ m/s

Slow Speed (PWS – 30%) = 0.70 × Pref_Avg = _____ m/s

Medium Speed (PWS) = 1.00 × Pref_Avg = _____ m/s

Fast Speed (PWS + 30%) = 1.30 × Pref_Avg = _____

Appendix C: Marker Locations

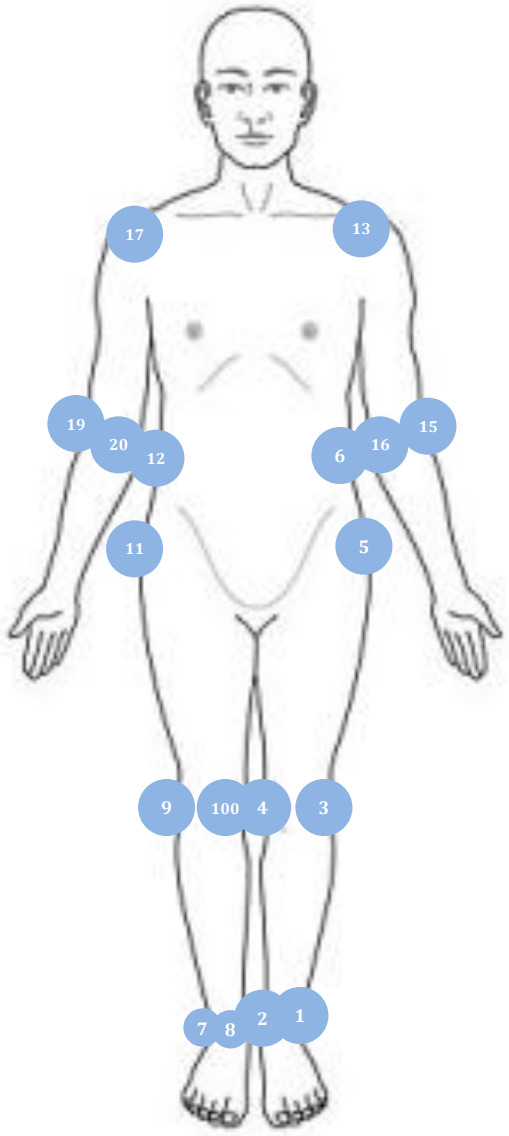


Physical Markers

1. LFHL – Left forehead – use the headband
2. RFHD – Right forehead – use the headband
3. LBHD – Left backhead – use the headband
4. RBHD – Right backhead – use the headband
5. C7 – C7 vertebrae
6. T8 – T8 vertebrae
7. RBAC – Right back (locate on the scapula, there is no specific landmark)
8. STRN – Sternum – Top of sternum
9. XYPH – Xyphoid process
10. LSHO – Left shoulder (acromioclavicular joint, boney protrusion on the top of shoulder)
11. LUA1 – Left upper arm (lower ½ of upper arm) 1 – placed at top of tricep
12. LUA2 – Left upper arm (lower ½ of upper arm) 2- placed below and toward bicep from 1 (see picture)
13. LUA3 – Left upper arm (lower ½ of upper arm) 3 – placed below 1, still on tricep
14. LFAL – Left forearm lateral
15. LFAM – Left forearm medial
16. LWRR – Left wrist – radius styloid process
17. LWRU – Left wrist – ulna styloid process
18. LFIN – Base of left middle finger
19. RSHO – Right shoulder (acromioclavicular joint, boney protrusion on the top of shoulder)
20. RUA1 – Right upper arm (lower ½ of upper arm) 1 – placed at top of tricep
21. RLUA2 – Right upper arm (lower ½ of upper arm) 2- placed below and toward bicep from 1 (see picture)
22. RUA3 – Right upper arm (lower ½ of upper arm) 3 – placed below 1, still on tricep

23. RFAL – Right forearm lateral
24. RFAM – Right forearm medial
25. RWRR – Right wrist – radius styloid process
26. RWRU – Right wrist – ulna styloid process
27. RFIN – Base of right middle finger
28. LASI – Left anterior superior iliac spine
29. RASI – Right anterior superior iliac spine
30. LASI_2 – Left iliac crest
31. RASI_2 - Right iliac crest
32. LPSI – Left posterior superior iliac spine
33. RPSI – Right posterior superior iliac spine
34. LTH1 – Left thigh (4 marker combo) see picture for layout
35. LTH2 - left thigh (4 marker combo)
36. LTH3– left thigh (4 marker combo)
37. LTH4– left thigh (4 marker combo)
38. LSK1 – Left shank (4 marker combo) See picture for layout
39. LSK2– Left shank (4 marker combo)
40. LSK3– Left shank (4 marker combo)
41. LSK4– Left shank (4 marker combo)
42. LHEE – Left heel (back of heel on shoe)
43. LLHL – left lateral heel (on shoes)
44. L5MT – left foot, base of 5^{th} toe (metarsal) – on top of shoe (Tape on)
45. LTOE – base of left big toe on top of shoe
46. RTH1 – right thigh (4 marker combo) see picture for layout
47. RTH2 - right thigh (4 marker combo)
48. RTH3– right thigh (4 marker combo)
49. RTH4– right thigh (4 marker combo)
50. RSK1 - Right shank (4 marker combo) See picture for layout
51. RSK2–Right shank (4 marker combo)

52. RSK3– Right shank (4 marker combo)
53. RSK4– Right shank (4 marker combo)
54. RHEE– Right heel (back of heel on shoe)
55. RLHL – Right lateral heel (on shoes)
56. R5MT - Right foot, base of 5th toe (metarsal) – on top of shoe (Tape on)
57. RTOE - Base of right big toe on top of shoe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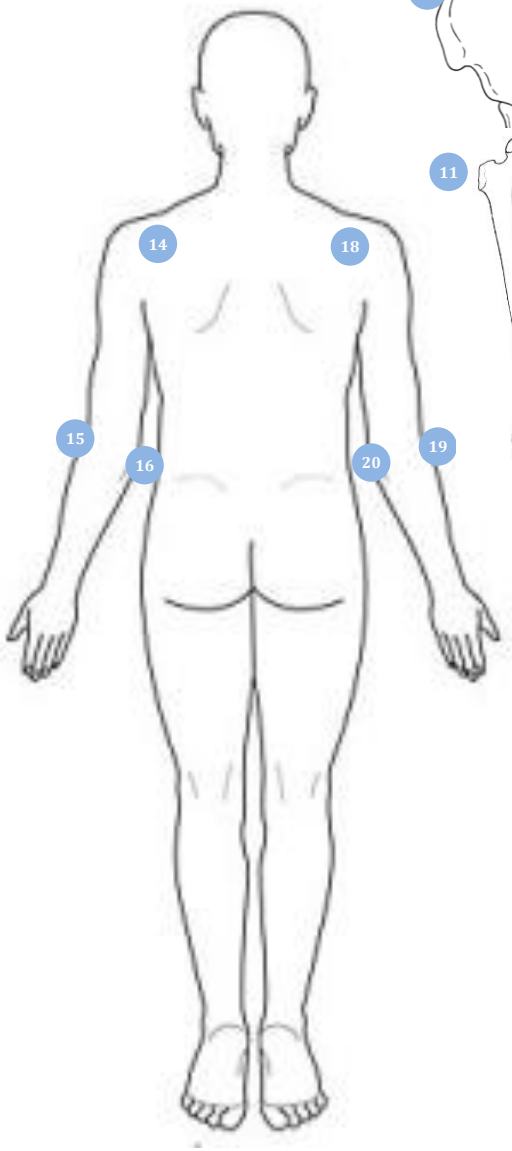
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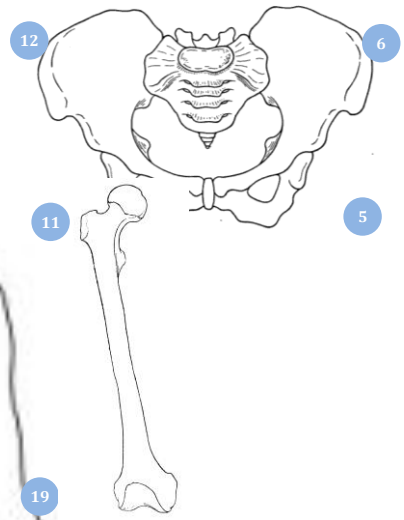
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Digital Markers

1. LANL – Left lateral ankle
2. LANM – Left medial ankle
3. LKNL – Left lateral knee
4. LKNM – Left medial knee
5. LGTR – Left greater trochanter
6. LILL – Left iliac crest
7. RANL – Right lateral ankle
8. RANM – Right medial ankle
9. RKNL – Right lateral knee
10. RKNM – Right medial knee
11. RGTR – Right greater trochanter
12. RILL – Right iliac crest
13. LSHA – Left anterior shoulder
14. LSHP – Left posterior shoulder
15. LELL – Left lateral elbow
16. LELM – Left medial elbow
17. RSHA – Right anterior shoulder
18. RSHP – Right posterior shoulder
19. RELL – Right lateral elbow
20. RELM – Right medial elbow

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