EFFECT OF PARKINSON'S DISEASE ON THE STEP RESPONSE TO A BACKWARDS PULL

BY

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Abstract

The goal of this study was to identify parameters of balance recovery that may be sensitive to postural instability early in the progression of Parkinson's disease. The response to a backwards pull was analyzed in a group of healthy controls and a group of adults diagnosed with mild Parkinson's disease. Video, motion, EMG, and force plate data were collected and analyzed. The effect of Parkinson's disease on strategy (single or multiple step response, number of steps, step foot), temporal (reaction time, weight shift time, step duration), kinematic (step length, step height, ankle angle), kinetic (peak ankle torque, peak landing force) and center of pressure (location at liftoff and landing) parameters were examined for the first step in the response. In the PD group, subjects were less consistent in their choice of stepping limb over multiple trials, but did not take more steps or use a multiple step strategy more frequently than the controls. The PD group had a longer weight shift time, but had similar reaction times and step duration times compared to HC. The PD group showed different motion at the ankle joint prior to liftoff and were in dorsiflexion at liftoff whereas the HC were in plantarflexion. HC and PD showed similar ankle motion after liftoff. There were no differences in peak torques or peak landing force between the two groups; however the center of pressure was further posterior at landing in the PD group. These results suggest that further investigation focused on the movement preparation stage may be able to identify early markers of postural instability. Further study is also necessary to determine the relationship between these parameters and clinically defined postural instability.

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CHAPTER ONE: INTRODUCTION

Background and Motivation

Postural instability is a significant problem in Parkinson's disease (PD) and can eventually lead to falls. Unfortunately, the clinical tools available to assess postural instability are not sensitive enough to predict those who are at an increased risk of falling before a fall occurs. If a laboratory or clinical assessment could be developed that is sensitive enough to detect postural instability early in the disease progression, then interventions targeting fall risk could be developed to reduce the risk of falling.

Falls have a devastating effect on quality of life and the current evaluations of fall risk are inadequate. The risk of falling in individuals with PD is more than double that of the general elderly population and the consequences of a fall can have severe impacts on quality of life including fractures, hospitalization, fear of falling, loss of independence, and restriction of activities [1-3]. The retropulsion test, one component of the Unified Parkinson's Disease Rating Scale (UPDRS), is used to assess postural instability. However, this test has not been shown to be predictive of fall risk. Several common characteristics have been identified within PD patients with an increased

risk of falling, but they have not been developed into a predictive tool. Currently the best predictor of future falls is a history of falls.

Balance-related parameters are likely to be important in detecting the early signs of postural instability. Studies investigating the step response to a balance disturbance have described response changes associated with increased fall risk. Significant changes in strategy, temporal, kinematic, and kinetic parameters with age, fall history, and PD have been found. However, studies in PD have investigated this response only late in the disease progression when postural instability is already clinically recognized. The step response to a balance disturbance has not been studied early in the progression of PD, which is the time period when the clinician has the best opportunity to delay the first fall by introducing an effective intervention.

Effective interventions exist for those at high risk of falling. In the healthy elderly population, multi-factorial programs have been shown to reduce fall risk by almost 70% [4]. In PD, compensatory step training has been shown to reduce falls by 50% [5]. Therefore, there is reason to think that targeted interventions may reduce the risk of falling in persons with PD if those at increased risk could be identified prior to a fall occurring.

Specific Aims

The goal of this study was to identify balance recovery parameters that may be sensitive to the presence of postural instability early in the progression of Parkinson's disease, prior to clinical detection of postural instability. Video, motion,

EMG, and force plate data were collected and analyzed to characterize the response to a backwards waist pull of two groups: participants with mild PD while on their PD medication and age range matched healthy control participants. The response was characterized by response strategy parameters (single vs. multiple step response, number of steps, step foot consistency), temporal parameters (reaction time, weight shift time, step duration), kinematic parameters (step length, step height, ankle angle), kinetic parameters (peak ankle torque, peak vertical force), and center of pressure parameters (COP position) during the first step.

The short term goal of this study was to determine balance-related parameters that are sensitive to postural instability early in the progression of Parkinson's disease. This will allow the design of follow-up studies to determine if these parameters are sensitive and specific enough to be used as fall risk predictors in persons with PD. The long term goal of this research is to better understand the reasons for increased fall risk in Parkinson's disease leading to the development of more predictive clinical fall risk assessment tools and the development of more effective interventions to reduce fall risk.

Thesis Content

This document contains four chapters. Chapter 1 consists of an introduction to the area of study. Chapter 2 consists of an extensive background survey of relevant literature published. Chapter 3 consists of a manuscript reporting the background,

methods, and results of the study investigating the effects of Parkinson's disease in

the step response to a backwards pull. Chapter 4 consists of a summary of this study.

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CHAPTER TWO: BACKGROUND

Parkinson's Disease

Parkinson's disease (PD) is a neurodegenerative disorder first described by James Parkinson in 1817 and is estimated to affect over 1.5 million people in North America [6, 7]. The prevalence of PD increases with age, but there are currently no other risk factors or accurate predictors of who is at risk, although it has been shown to have a higher prevalence rate in developed countries. PD progressively affects mobility and independence, ultimately resulting in an increase in mortality rate of 2-5 times [8]. There is no treatment that slows or stops the progression of the disease.

Diagnosis. Diagnosis for PD is given through examination by a neurologist or movement disorders specialist. The presence of a resting tremor, asymmetry of symptoms, and a positive response to Levodopa therapy are an indication of the presence of Parkinson's disease. Physiologically, PD is characterized by the progressive death of dopaminergic neurons in the basal ganglia, specifically in the substantia nigra. It is estimated that 60-70% of these neurons have already been lost at the onset of symptoms [9].

Severity Rating Scales. Parkinson's disease is a progressive disease, and there are two severity rating scales currently in use to quantify its progression: The Unified Parkinson's Disease Rating Scale (UPDRS) and the Hoehn and Yahr scale. The Hoehn and Yahr scale was developed in 1967 by Margaret M. Hoehn, MD and Melvin D. Yahr, MD. The Hoehn and Yahr scale consists of 5 stages to assess the degree of disability due to Parkinson's symptoms [10]:

Stage 1:   Unilateral involvement, minimal or no functional impairment.

Stage 2:   Bilateral or midline involvement, without impairment of balance.

Stage 3:   First sign of impaired righting reflexes possibly seen as unsteadiness as the patient turns, or loss of balance when pushed from standing with eyes closed and feet together. Functionally restricted in activities, possibly still able to work, physically capable of being independent, disability is mild to moderate.

Stage 4:   Fully developed, severely disabling disease; patient is still able to walk and stand unassisted but is markedly incapacitated.

Stage 5:   Confinement to bed or wheelchair unless aided.

The Unified Parkinson's Disease Rating Scale was developed in 1987 and consists of 3 sections: a mentation, behavior and mood section; an activities of daily living section; and a motor section. In each section, the examiner scores the patient on a scale of 0-4 on several questions, with 0 being normal and 4 representing the worst possible case for that question. The motor section consists of questions for the patient as well as several quick physical tests such as finger taps, rising from a chair,

a postural stability test (called the retropulsion test or pull test), and rigidity tests where the examiner passively moves the limbs to assess rigidity. The scores for each question are added to determine the total score, with the maximum being 200. Scores are not typically given to the patient, but are used by the clinicians to track the progression of the disease.

Pathophyisology

Anatomy of the Basal Ganglia. The basal ganglia are located beneath the cerebral cortex and consist of five nuclei: the *globus pallidus*, *caudate nucleus*, *putamen*, *subthalamic nucleus*, and *substantia nigra*. The globus pallidus is divided into an internal and external region, and the substantia nigra is divided into two regions: the dorsal (pars compacta) and ventral (pars reticulata) regions. The caudate nucleus and putamen are often referred to together as the *striatum* [11, 12].

Function of the Basal Ganglia. The basal ganglia are indirectly involved in movement. The basal ganglia are important in preparing the body for voluntary movement. They process information needed for planning, triggering, and organizing the postural adjustments associated with a voluntary movement. The basal ganglia also "allow" movement in a sense, by disinhibiting agonist muscles and inhibiting antagonist muscles. The basal ganglia are also involved in sequencing movements and motor learning [11, 12].

Neurophysiology of the Basal Ganglia. The basal ganglia receive input at the striatum

from the cerebral cortex, thalamus, and brain stem. Output from the basal ganglia

leaves from the globus pallidus internal region or the substantia nigra pars compacta

region. The main output is to the cerebral cortex via the thalamus although it also

outputs to the brain stem. The basic basal ganglia-thalamo-cortical loop consists of

input from cerebral cortex→striatum→globus pallidus and/or substantia

nigra→output to thalamus. All output from the basal ganglia is inhibitory. This loop

is somatatopically organized, so that certain parts of the cortex project to certain parts

of the striatum [11, 12]. There are thought to be two main pathways through the basal

ganglia. The direct pathway is thought to facilitate movement. The indirect pathway

is thought to inhibit movement and contains an extra loop involving the subthalamic

nucleus. The basal ganglia use several different neurotransmitters, but the loop

between the substantia nigra pars compacta and striatum is the dopaminergic loop that

is affected in Parkinson's disease.

Parkinson's disease and the Basal Ganglia. The basal ganglia contain 80% of the

total dopamine in the brain [11, 12]. Parkinson's disease is caused by the death of

these dopaminergic neurons that project between the striatum and the substantia nigra

pars compacta. Loss of these projections causes increased activity in subthalamic

nucleus neurons which leads to increased activity of inhibitory pallido-thalamic

neurons. This leads to suppression of thalamic activity, ultimately leading to

suppression of cortical motor areas. By the onset of symptoms in Parkinson's disease,

60-70% of the dopaminergic projections have been lost in the ventrolateral tier of the

substantia nigra pars compacta [9]. Figure 2-1 illustrates the basal ganglia circuitry

and what is different in Parkinson's disease.
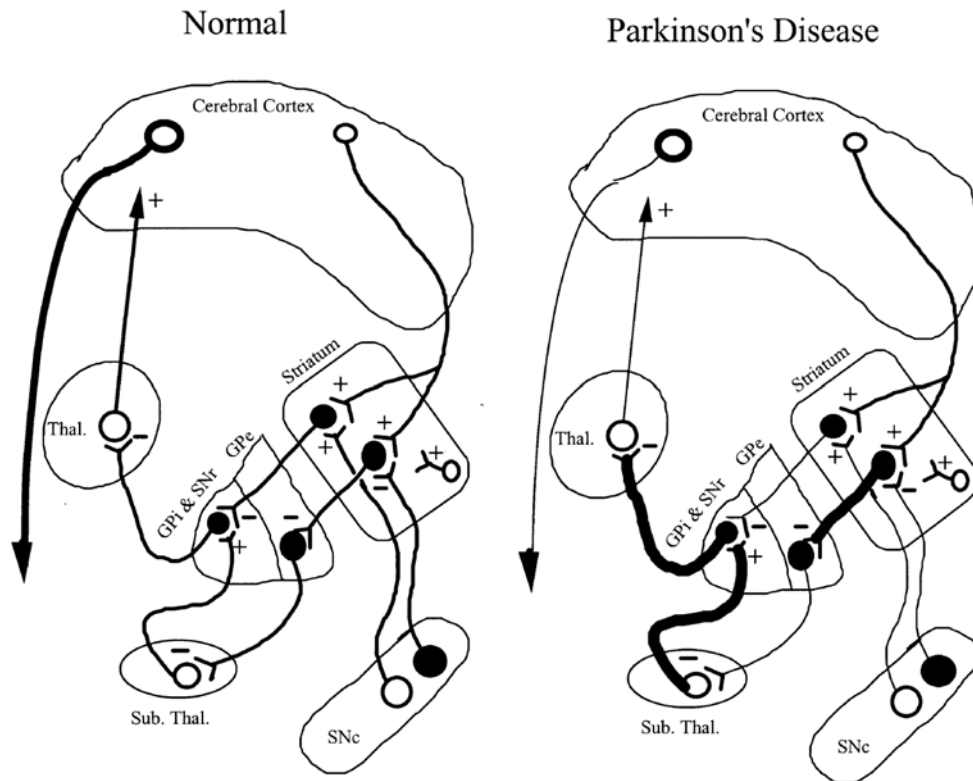
Figure 2-1. Abnormalities in neural activity in Parkinson's Disease. Notice that abnormalities in activity in basal ganglia structures lead to increased inhibitory activity in the thalamus, leading to decreased excitatory input to the cerebral cortex and suppression of the motor cortical areas. Thal: thalamus; GPi/GPe: globus pallidus internal/external; SNr/Snc: substantia nigra pars reticulata/pars compacta; Sub. Thal: subthalamic nucleus. Plus (+) indicates excitatory connection, minus (-) indicates inhibitory connection. In right figure, bold black lines indicate increased activity, thin lines indicate reduced activity. *Figure courtesy of Dr. Paul Cheney.*

Symptoms of Parkinson's Disease

The loss of dopaminergic input from the substantia nigra pars compacta causes increased activity in the indirect pathway (which inhibits movement) and decreased activity in the direct pathway (which facilitates movement). Both of these situations lead to decreased activity of the motor cortex, leading to the common symptoms of Parkinson's disease.

Bradykinesia. Bradykinesia refers to slowed and sometimes incomplete movements. Akinesia refers to a lack of movement. Bradykinesia and akinesia are seen in the expressionless appearance of the face, shuffling gait, and difficulty initiating movements [12]. These are thought to be due to the loss of the dopaminergic neurons in the direct pathway, resulting in increased inhibition of the motor cortex [11, 12].

Tremor and Rigidity. Parkinson's disease is characterized in part by a resting tremor at about 4-6 Hz. Rigidity is manifested as an increased muscle tone resulting in resistance to passive movements. These are examples of abnormal motor activation due to input from affected projections in the indirect pathway [11, 12].

Postural Instability. Postural instability refers to the impaired balance and coordination often seen in those with Parkinson's disease. Postural stability requires proper sensory organization, appropriate motor adjustments to prepare, execute, and adjust a movement, and appropriate background muscle tone [13]. Patients with PD

often have abnormal postural preparations prior to a voluntary movement, have increased sway when standing still, and have abnormal reactions to an external perturbation. They are also less able to adapt a postural response to a change in support condition [14]. Postural instability combined with other PD symptoms leads to an increased risk of falling in those with Parkinson's disease.

Therapy

There are currently no treatments that have been shown to slow or stop the progression of Parkinson's disease. However, therapies do exist that improve the motor complications associated with the disease.

Levodopa Therapy. The first effective drug therapy for PD is Levodopa, which was introduced 30 years ago. Levodopa is effective in lessening the severity of symptoms, and is effective initially in over 90% of patients [6, 9]. Levodopa is a dopamine therapy, working to replace dopamine that has been lost in the brain. Levodopa improves several parkinsonian symptoms such as bradykinesia, rigidity, and tremor. It has been shown to improve the control of force and sequencing of muscle activations in centrally initiated postural adjustments [15].

While Levodopa does improve several symptoms, it is not a perfect therapy and its long term effects remain unknown [16, 17]. There are concerns with chronic use of Levodopa and there are several symptoms that do not respond to Levodopa treatment. In particular, motor deficits in PD such as postural instability, freezing of

gait, and swallowing problems have been shown to be resistant to Levodopa treatment [16, 18]. In a postural sway study by Rocchi *et al.* it was shown that Levodopa treatment actually increased abnormalities in sway, and subjects performed better when off medication [15]. In another study on the effects of Levodopa, subjects receiving the highest dose had significantly more dyskinesia, hypertonia, infection, headache, and nausea as compared to controls on placebo [17].

There are several concerns about the effects of chronic use of Levodopa including increased dyskinesia, mental changes, and motor fluctuations. Up to 50% of patients will experience inconsistent results of taking the Levodopa dose after 2-5 years, and as the disease progresses it becomes less effective. Some patients experience a wearing off effect between doses; others respond normally to the medication for a period, followed by periods of minimal response. This inconsistency is referred to as a motor fluctuation, and the prevalence increases with increasing severity of disease and length of treatment [16].

Deep Brain Stimulation. Deep Brain Stimulation (DBS) has emerged as an alternative to Levodopa treatment for Parkinson's disease. This treatment involves high frequency stimulation through electrodes placed in the subthalamic nucleus or globus pallidus of the basal ganglia. This treatment has been shown to improve postural control, where Levodopa treatment falls short. This is most likely because DBS can affect non-dopaminergic pathways, which are thought to be increasingly affected by Parkinson's disease [19]. However, its relative effectiveness is still controversial due

to the interactions of DBS and other therapies and the fact that the mechanism of how and why it works is not fully understood.

Postural Instability

Postural control can be described with three parameters- the center of mass, center of pressure, and base of support. The center of pressure is the point where the resultant ground reaction force for the body acts. The base of support is the area circumscribed by the support surface (the feet when standing). The center of pressure changes constantly to account for the change in location of the center of mass. For stability, the center of mass should not leave the base of support, so the center of pressure is constantly moving around to make sure this does not happen [12].

The brain receives and processes different types of cues about the position of the body and its stability. The vestibular system provides signals related to the orientation and movement of the head in space. The organs of the vestibular system are located in the inner ear. The somatosensory system provides signals gathered from the skin and deep pressure sensors in the body and includes touch, pain, pressure, temperature, and proprioception [12, 20]. Visual information is another source of postural information. Postural stability requires the proper processing of information from all of the sensory systems, appropriate motor adjustments to prepare, execute, and adjust a movement, and appropriate background muscle tone [13].

Falls in Parkinson's Disease. Falls have a devastating impact on quality of life and Parkinson's disease greatly increases the risk of falling. The exact mechanism by which motor problems associated with PD interact to influence falling is not known, but it is clear that the risk of falling is increased. Approximately 30% of the general elderly population will fall in a given year. In Parkinson's disease, this risk has been shown to increase to between 46%-68% [1, 21-24]. This is significant because the consequences of a fall can have severe impacts on quality of life including fractures, hospitalization, loss of independence, and restriction of activities [1-3]. In a recent retrospective study of 1,092 Parkinson's patients by Wielinski *et al.*, 65% of those who fell sustained an injury, 22% of those who fell sustained fractures, and 41% of those sustaining fractures required surgery. In addition, approximately 27% of the entire study group required health care services as a result of falling. This indicates substantial costs associated with falling in Parkinson's disease [22]. Other studies have echoed this increased risk of falling and increased risk of injury in Parkinson's disease [21]. In addition to the severe consequences of injurious falls, a fear of falling (with or without a previous fall) has been shown to be associated with increased fall risk as well as indicating a reduced quality of life in older adults [3, 25].

Fear of Falling. Fear of falling is even more prevalent in Parkinson's disease than in the general elderly population and may or may not stem from actually experiencing a fall [3, 25]. This fear can have a significant impact on quality of life as well as on the risk of falling. In addition to added general stress, fear of falling impacts quality of

life by causing the person to restrict physical and social activities they would normally participate in [3]. Tinetti *et al.* developed the Falls Efficacy Scale in order to more precisely determine the relationship between fear of falling and actual functioning. They found that falls efficacy was strongly associated with tests of functioning and that a person's perception of capability influences behavior, regardless of the actual capability. In addition, they found that about 15% of subjects who had never fallen reported a decrease in activity due to a fear of falling, indicating an unnecessary decline in quality of life [3].

In addition to the quality of life impacts, fear of falling has also been associated with an increase in fall risk [26-28]. This may be due to the decrease in activity, a change in postural stability due to increased caution, or a change in balance strategy. The exact interaction between fear of falling and postural instability is still unknown.

Assessment of Fall Risk. Studies have investigated fall risk factors in both healthy elderly and PD populations in an attempt to find a fall risk predictor. While several biomechanical and physiological measures have been found to be associated with falling, no one factor or combination of factors has been found to predict falling. In the healthy elderly population, lower muscle power or strength in the lower extremities, worsened postural control and lateral balance, vision impairments, the use of multiple medications, cognitive impairment, gait abnormalities, and impaired performance on a few clinical balance tests have been found to be associated with

falling [29-34]. However, none of these factors have been shown to identify fallers prior to a fall occurring. Thus, the best predictor of a future fall is still a history of falls.

Several common characteristics have been identified within PD patients with an increased risk of falling: a history of previous falls, increased disease severity and duration, depression, dementia, and urinary incontinence [21, 23, 24, 35]. In addition, the presence of dyskinesias, freezing episodes, loss of arm swing, fear of falling, poorer scores on several measures of the UPDRS test, poor performance on clinical measures of motor planning, fine motor control, limb coordination, and gait have also shown to be associated with a history of falls [21, 23, 24, 27, 35-37]. However, as in the elderly population, these factors have not been able to predict falling in those who do not have a history of falls. The difficulty in determining a single clinical test to evaluate fall risk most likely has to do with the multi-factorial causes of falls and the many different circumstances in which falls occur [38]. In Parkinson's disease, postural instability is a major cause of falls and is specifically tracked as part of the UPDRS evaluation.

Assessment of Postural Instability. Postural instability is one of the cardinal symptoms of Parkinson's disease and may lead to falls [39]. The retropulsion test (sometimes called the pull test) is widely used to assess postural instability in Parkinson's disease. In this test, which is part of the United Parkinson's Disease Rating Scale (UPDRS) evaluation, the clinician provides a sudden backwards pull to

the patients' shoulders and visually assesses the resulting balance response. Problems associated with this test include problems with reliability in executing and scoring the test. For example, some examiners warn patients about the pull and perform it several times, while others provide no warning and perform it only once. The patient's response is scored on a course scale of 0-4 defined as follows: 0: normal, 1: recovers unaided, 2: would fall if not caught, 3: unstable, loses balance spontaneously, 4: unable to stand unassisted. The rating scale does not have a specific definition of a normal response or a cutoff response that indicates high fall risk. It is implied that those at a higher risk of falling require more steps to maintain their balance, while those at a lower risk require fewer steps. This test has been shown to be sensitive to differences between PD patients with and without a history of falls, however most of those studies involve severe cases of PD who already exhibit major balance problems and it is not predictive of fall risk [27, 38, 40, 41].

Recently, more quantitative laboratory tests have shown promising results in detecting postural instability earlier in the progression of PD. One study of 55 subjects with mild to moderate severity PD showed that an increased medial-lateral sway, increased sway area, and a more forward position of the center of pressure discriminated them from healthy controls [36, 42]. Another recent sway study of 215 PD patients found that an increased sway area was an independent risk factor for recurrent falling in PD [36]. So, there is reason to believe that balance-related parameters may provide insight into postural instability early in the disease progression.

Balance Recovery

The ability to recover balance after an unexpected perturbation is essential to preventing a fall. Studies have shown that with age and certain pathologies, strategies for balance recovery change. When presented with a balance perturbation there are two types of responses. A fixed-support response is when balance is recovered without moving the base of support. Included in this category are the ankle and hip response strategies, which involve rotating at the ankle or hip to maintain balance without moving the base of support. A change-in-support response is evoked when the perturbation is large enough that the fixed-support responses are not as effective. This usually involves changing the location and configuration of the base of support. A stepping response often requires the use of an anticipatory postural adjustment, where the body weight is shifted to the stance limb prior to liftoff of the stepping limb [43].

Differences in the stepping response have been widely studied in the elderly population, who also has an increased risk of falling. Older adults tend to resort to a stepping strategy at smaller disturbances than young, they tend to take multiple, shorter steps, and tend to step laterally in response to an anterior or posterior perturbation [44-47]. In addition, they show larger peak ankle and hip torque and power [48, 49], reductions in hip flexion, knee flexion and extension, and ankle plantarflexion velocity [50]. Elderly subjects with a history of falls showed smaller peak ankle torque, slower reaction time, and slower rate of ankle torque development

in response to a forward lean and release perturbation [51], and also tended to step

laterally in response to a backwards pull [44].

Studies have also investigated deficits in the sway response in Parkinson's

disease. Most of these studies have involved subject populations who are moderately

to severely affected by the disease and often off medications. In fact, several studies

have specifically chosen their subject population because of difficulties with balance

[14, 41, 52, 53]. These studies have been helpful in determining which aspects of

balance are affected by PD. For instance, PD introduces abnormal foot-floor reaction

forces, muscle activation patterns, and inflexibility in the feet-in-place response to

surface translations [13, 54].

The step response to a balance perturbation has also been investigated in

Parkinson's disease. Jacobs *et al.* have found that moderate and severe PD subjects,

when off medication, show differences in response compared to healthy controls.

They use shorter than normal steps, use multiple anticipatory postural adjustments,

have a longer step foot liftoff time, and are less consistent in the choice of stepping

limb in the response to a backwards surface translation. This altered response may be

due to an inability to quickly select an appropriate response since young exhibit

similar behavior when they are unable to pre-select the stepping foot [53, 55].

Kinematic and kinetic studies during functional tasks in persons with PD have

shown significant differences in those parameters during gait, step initiation, and sit-

to-stand tasks. In gait, moderately affected PD subjects on medication showed smaller

ankle range of motion during the push off and swing phases, and smaller peak

plantarflexion at toe off and in the swing phase [56]. In gait initiation, moderate to severely affected PD subjects off medication showed decreased force production, decreased velocity, and slowed execution of anticipatory postural adjustments [57]. In a sit-to-stand task, moderately affected PD subjects on medication showed smaller hip flexion torque and slower time to peak torque in the ankle, knee, and hip [58]. The differences in kinetics and kinematics during functional tasks may describe certain deficiencies that put the PD population at a higher risk of falling. Unfortunately these parameters are not well understood for the step response used to recover from a balance perturbation.

It is important to note that studies in Parkinson's disease have investigated the step response only late in the disease progression when postural instability is already clinically recognized. The step response to a balance perturbation has not been studied early in the progression of Parkinson's disease, prior to the presence of clinically measured postural instability (H&Y ≤ 2). Since interventions exist for those at increased risk of falling, and the consequences of even one fall are severe, it is important to determine the appropriate time to begin an intervention targeting fall risk.

Interventions to Reduce Fall Risk

Effective interventions exist for those at high risk of falling. In the healthy elderly population, multi-factorial programs together with targeted individual therapies are the most effective in fall prevention [4]. These programs typically

include exercise and physical therapy, gait and balance training, advice on proper use of assistive devices, review and modification of medications, treatment of postural hypotension, modification of environmental hazards, and targeted medical assessments. Individual interventions are then determined based on the factors most prevalent in the patient. These multi-factorial interventions have reduced fall risk by up to 66% [4].

A similar multi-factorial approach is probably necessary to reduce fall risk in persons with PD. Studies have investigated the effects of physical therapy and balance and gait training on PD fallers, and while they have not been able to conclusively prevent falls, they have seen improvements in balance and gait measures [59-61]. Stankovic *et al.* studied the effect of physical therapy on balance in healthy elderly, PD fallers, and PD non-fallers [60]. Physical therapy including regular physical activity, walking with a visual stimulus, stepping, playing recreational sports, strategies for correction of motor function such as attention, maintaining an upright posture, and elongation of muscles was applied for 30 days. Balance measures included quiet standing tasks, internal perturbation tasks, and an external perturbation. This study showed that the physical therapy program improved all of the balance measures, especially the tandem stance, single leg stance, functional reach, step, and external perturbation tests. While this study was not able to show the effect on falls, it did find an improvement in some of the measures that are used to assess fall risk.

Other studies on gait and compensatory step training in PD have shown improvements in both gait and step parameters and one study showed a 50% decrease in falls in the group that received the intervention [5, 59]. Therefore, there is reason to think that targeted interventions may reduce the risk of falling in persons with PD.

Summary

Parkinson's disease is a debilitating disease and postural instability leading to falls is one of the most disabling symptoms. Experiencing a fall severely impacts quality of life on physical, economic, and psychological levels. While there are effective interventions that reduce fall risk, they are often not implemented until after the first fall due to the lack of a predictive measure. If laboratory or clinical assessments were available to identify the appropriate time to begin targeted interventions, fall risk could be significantly reduced. Prevention of that first fall would allow persons with Parkinson's disease to maintain an independent and active lifestyle as long as possible.

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CHAPTER THREE: STUDY

Abstract

Background. Postural instability leading to falls is one of the most disabling

symptoms of Parkinson's disease (PD) and the current methods available to assess

postural instability are not sensitive enough to predict those at higher risk of falls.

This study sought to investigate parameters of balance recovery that may be sensitive

to postural instability early in the progression of Parkinson's disease.

Methods. The response to a backwards pull was measured in a group of adults

diagnosed with Parkinson's disease (PD: age range 48-77, mean age 63.2 ± 8.9 years,

H&Y 2) and a group of age-range matched, healthy controls (HC: age range 48-79,

mean age 68 ± 11 years). Video, motion, EMG, and force plate data were collected

and analyzed. The effect of Parkinson's disease on strategy (number of steps, step

foot), temporal (reaction time, weight shift time, step duration), and kinematic/kinetic

(step length, step height, ankle angle, peak ankle torque), and center of pressure

(location at liftoff and landing) parameters were examined for the first step in the

response to a backward waist pull.

Results. The PD group was less consistent in their choice of stepping limb across

multiple trials, but did not take a larger number of steps or use a multiple step strategy

more frequently than the controls. The PD group had a longer weight shift time, but had similar reaction times and step duration times. The PD group utilized a different motion at the ankle joint prior to liftoff. At liftoff, the PD subjects were in dorsiflexion, whereas the HC subjects were in plantarflexion. No group differences were observed in ankle joint motion after liftoff, in the peak ankle torques, or in the peak landing forces. However, the center of pressure was located further posterior at landing of the first step in the PD group, compared to the HC group.

Conclusions. These results demonstrate that biomechanical indicators of postural instability may be present in the initial movement preparation stage in the response, which is the time period between disturbance onset and liftoff time of the first step. Future studies should further investigate this stage in the response and should investigate the relationship between these parameters and postural instability.

Introduction

Postural instability is a significant problem in Parkinson's disease (PD) and eventually leads to falls. Unfortunately, the clinical tools available to assess postural instability are not sensitive enough to predict those who are at an increased risk of falling before a fall occurs. If laboratory or clinical assessments could be developed that are sensitive enough to detect postural instability early in the disease progression, then interventions targeting fall risk could be developed to reduce the risk of falling. This study aims to identify parameters related to balance recovery that may be

sensitive to postural instability prior to the presence of clinically recognized postural instability in Parkinson's disease.

Clinical Need. Falls have a devastating effect on quality of life and the current evaluations of fall risk are inadequate. The risk of falling in individuals with PD is more than double that of the general elderly population, with up to 68% of patients falling per year [1-4]. The consequences of a fall can have severe impacts on quality of life including fractures, hospitalization, loss of independence, and restriction of activities [2, 5, 6]. Given the physical, psychological, and economic impacts of falling, it is important to be able to assess risk and prescribe appropriate therapies and interventions. While great strides have been made in treatment of most PD symptoms, postural instability is often unresponsive to medications and no tool currently exists to accurately predict fall risk.

The current methods available to assess postural instability are not sensitive enough to predict those at a higher risk of falling before a fall occurs. The retropulsion test is widely used to assess postural instability in Parkinson's disease. However, problems associated with this test include reliability in executing and scoring the test. For example, some examiners warn patients about the pull and perform it several times, while others provide no warning and perform it only once. In addition, the patient's response is scored on a course scale of 0-4 defined as follows: 0: normal, 1: recovers unaided, 2: would fall if not caught, 3: unstable, loses balance spontaneously, 4: unable to stand unassisted. This test has been shown to be

sensitive to differences between PD patients with and without a history of falls, however many of those studies involve only cases of PD who already exhibit balance impairments and the retropulsion test is not predictive of fall risk [7-10]. More recent studies with larger sample sizes and a wider range of severity levels have shown promising results in detecting postural instability in early PD using laboratory measures of postural sway [11, 12].

Interventions to Reduce Fall Risk. Effective interventions exist for those at high risk of falling. In the healthy elderly population, multi-factorial programs together with targeted individual therapies are the most effective in fall prevention and have reduced fall risk by up to 66% [13]. Multi-factorial programs combine several therapies such as physical therapy, strength and balance training, and home modifications to affect the multi-factorial causes of falls. A similar approach is probably necessary to reduce fall risk in persons with PD. Studies on gait and compensatory step training in PD have shown improvements in both gait and step parameters and one study showed a 50% decrease in falls after the intervention [14, 15]. Therefore, there is reason to think that targeted interventions will reduce the risk of falling in persons with PD if those at increased risk could be identified prior to a fall occurring.

Assessment of Fall Risk. There is currently no tool to accurately predict fall risk. However, several common characteristics have been identified within PD patients

with an increased risk of falling: a history of previous falls, increased disease severity

and duration, depression, dementia, and urinary incontinence [1, 16-18]. In addition,

the presence of dyskinesias, freezing episodes, loss of arm swing, fear of falling,

poorer scores on several measures of the Unified Parkinson's Disease Rating Scale

(UPDRS), poor performance on clinical measures of motor planning, fine motor

control, limb coordination, and gait have also been shown to be associated with a

history of falls [1, 9, 11, 16-19]. However, none of these factors have been shown to

identify fallers prior to a fall occurring. Thus, the best predictor of a future fall is still

a history of falls.

Balance Recovery. Balance-related parameters are likely to be important in detecting

the early signs of postural instability. The ability to recover balance after an

unexpected perturbation is essential to preventing a fall. Significant changes in

strategy, temporal, kinematic, and kinetic parameters with age, fall history, and

Parkinson's disease have been found.

Studies into the feet-in-place response to surface translations have shown that

PD causes abnormal foot-floor reaction forces, muscle activation patterns, and

inflexibility [20, 21]. Kinematic and kinetic studies during functional tasks have

shown differences in those parameters during gait, step initiation, and sit-to-stand

tasks [22-25].

The step response to a balance perturbation has also been investigated in

Parkinson's disease. Jacobs *et al.* have found that PD subjects, compared to healthy

controls, use shorter than normal steps, use multiple anticipatory postural adjustments, have a longer step foot liftoff time, and are less consistent in the choice of stepping limb in the response to a backwards surface translation [26, 27]. This altered response may be due to an inability to quickly select an appropriate response since young exhibit similar behavior when they are unable to pre-select the stepping foot [28].

Studies into postural stability in Parkinson's disease have primarily focused later in the disease progression when postural instability is already clinically recognized or chosen their subject population specifically for balance deficits [10, 27, 29, 30]. The step response to a balance perturbation has not been studied early in the progression of Parkinson's disease, prior to the presence of clinically measured postural instability (Hoehn &Yahr ≤ 2). Since interventions exist for those at increased risk of falling, and the consequences of even one fall are severe, it is important to determine the appropriate time to begin an intervention targeting fall risk.

Differences in the stepping response have been more widely studied in the elderly population, which also has an increased risk of falling. Older adults tend to resort to a stepping strategy at smaller disturbances than young, they tend to take multiple, shorter steps, and tend to step laterally in response to an anterior or posterior perturbation [31-34]. In addition, they show larger peak ankle and hip torque and power [35, 36], reductions in hip flexion, knee flexion and extension, and ankle plantarflexion velocity [37]. Elderly subjects with a history of falls show smaller peak

ankle torque, slower reaction time, and slower rate of ankle torque development in response to a forward lean and release perturbation [38], and also tend to step laterally in response to a backwards pull [31].

Therefore, in our search for balance recovery parameters that may be sensitive to the onset of postural instability in individuals with PD, it seemed appropriate to investigate parameters related to strategy, temporal, kinematic, and kinetic aspects of the response. Once the most sensitive parameters have been identified, a follow-up study can be designed to establish the sensitivity and specificity of these parameters in detecting signs of early postural instability caused by PD.

Study Aims and Hypotheses. This study aimed to identify balance recovery parameters that may be sensitive to the presence of postural instability in people with Parkinson's disease early in the progression of the disease, prior to clinically measured postural instability. The response to a backwards waist pull was characterized in a group of PD participants at Hoehn & Yahr severity level 2, who by definition do not exhibit signs of postural instability, and a group of age-range matched healthy controls. Video, motion, EMG, force plate, and load cell data was collected and analyzed to characterize the response in terms of response strategy (single vs. multiple step response, number of steps, step foot consistency), temporal parameters (reaction time, weight shift time, step duration), kinematic parameters (step length, step height, ankle angle at liftoff and landing, peak ankle angle), kinetic parameters (peak ankle torque, peak vertical force), and center of pressure parameters

(COP position at liftoff and landing) during the first step. This was an exploratory study designed to determine which parameters of balance recovery justify further investigation in the search for early markers of postural instability.

Methods

Subjects. Ten subjects with idiopathic Parkinson's disease and 10 healthy controls (PD: age range 48-77, mean age 63.2 ± 8.9 years, H&Y 2; HC: age range 48-79, mean age 67.2 ± 10.9 years) were tested. All participants had a normal score on the Mini-Mental State Exam (MMSE) [39] and Beck Depression Index [40] and had mobility independent of any assistive devices. All participants gave informed consent for the study as approved by the Institutional Review Board at the University of Kansas Medical Center (KUMC). Study participants included persons qualifying for the study regardless of gender, race, or ethnic background.

Healthy controls were recruited using the Grayhawk database and from the community. Prospective healthy control participants were phone interviewed and asked to respond to a questionnaire concerning their health history. All healthy control participants were screened by a physical therapist, who was supervised by a geriatric physician specialist, using a medical history and a physical examination based on standardized cardiovascular, musculoskeletal and neurological evaluations. All healthy controls were living independently in the community and had no significant history of musculoskeletal, neurological, or cognitive impairments.

All PD participants were recruited from the KUMC Parkinson's Disease and Movement Disorder Center patient pool. Only those diagnosed with PD by the director of the Parkinson's Disease and Movement Disorder Center were considered for this study. Persons with atypical PD were not included. All PD participants were on dopaminergic medications and were tested in their best medication "ON" state. Patients who had undergone Deep Brain Stimulation (DBS) were excluded since it is unclear whether DBS positively or negatively affects balance. PD participants were given the UPDRS evaluation by a movement disorders specialist to ensure up-to-date scores. All PD participants had no other significant history of musculoskeletal, neurological, or cognitive impairments other than those associated with Parkinson's disease. All PD participants were Hoehn & Yahr 2 with UPDRS motor scores ranging from 9-38 (mean = 20).

Task. The participant stood in a comfortable upright position with arms crossed at the chest. The participant wore a safety harness connected to an overhead frame designed to prevent the participant from contacting the floor in the event of a fall and a research assistant stood behind the participant to ensure safety. The participant wore an adjustable but rigid waist harness attached in the back through a cable to the weight-drop mechanism which has been previously described [34]. When the mechanism was released, it delivered a posterior waist pull. The weight dropped was 20% body weight and the pull distance was equal to 8.7% of waist height, corresponding to a 5º equivalent disturbance angle [34]. The magnitude of the pull

was chosen to be large enough that the subject would have to utilize a step response to regain his/her balance. The participant was instructed to respond naturally to the posterior waist pulls. Trials were repeated until three good trials were obtained for all subjects.

Experimental Measurements. Video, Motion, force plate, EMG and load cell data were collected for each trial. Motion data were sampled at 120 Hz using reflective markers and a six camera Vicon 512 (Vicon Peak, Lake Forest, CA) motion analysis system. Markers were placed bilaterally on the 2nd metatarsal, lateral malleolus, heel, calf, and lateral femoral condyle. Muscle electromyographic data was measured using an eight channel Noraxon telemetered surface electrode system (Noraxon, Scottsdale, AZ). Electrodes were placed bilaterally on the tibialis anterior. Foot/floor reaction forces and moments were measured using three AMTI (Advanced Medical Technology Inc.; Watertown, MA) six-component force plates. A biaxial custom built load cell measured the forces in the cable attached to the waist harness.

Data Analysis. Motion data were filtered with a Woltring filtering routine (MSE=20) in the Vicon software, prior to being exported for post-processing. EMG data were full wave rectified. All analog data were sampled at 1080 Hz using a 16-bit A/D data acquisition system controlled with the Vicon workstation and filtered using a second order low pass Butterworth filter with a cutoff frequency of 50 Hz. Initial and final-time artifacts were minimized using forward and backward reflection of the data [41],

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and phase shift was eliminated by using forward and backward passes [42]. Data from all trials were processed using MATLAB (Mathworks, Natick, MA, USA).

Strategy parameters. Strategy parameters were determined by analyzing video taken during the trials. These parameters consisted of: the number of steps taken to regain balance, whether the subject used a single or multiple step response, and whether the subject was consistent in the foot used for each step (e.g. right or left). A subject was classified as using a multiple step response if they used more than one step to regain balance in any of the three trials. A subject was classified as being consistent in the choice of step foot if they used the same foot for the first step in all of the three trials. A step was defined as a change in the base of support which requires a foot liftoff and a translation of the foot.

Temporal parameters. Temporal parameters were determined by analyzing the load cell, force plate, EMG, and motion data. The load cell signal was used to quantify the disturbance onset, peak force, and impulse strength (area under the force-time curve). All temporal parameters are reported relative to the onset of the disturbance. A threshold method was used to determine the time when the muscle was activated. The EMG threshold value was defined as the mean plus five standard deviations of the signal over a 50 ms window prior to the disturbance. EMG onset time was defined as the first time when 25 consecutive data points exceeded the threshold. Reaction time was defined as the time between the disturbance onset and the first tibialis anterior

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muscle onset time. Liftoff time was defined as the time between the disturbance onset time and the unloading of the vertical force component under the foot used for stepping (vertical force < 3% body weight). Landing time was defined as the time between the disturbance onset and the time when the vertical force component under the landing foot increased to above the threshold (vertical force > 3% body weight). Weight shift time was defined as the time between reaction time and liftoff time. Step duration time was defined as the time between liftoff and landing time.

Kinematic and Kinetic Parameters: Step length was determined by the resultant distance traveled by the heel marker between the liftoff and landing times. Step height was defined as the maximum vertical displacement of the heel marker between liftoff and landing times. Step length and height are scaled to the subject's height.

Marker trajectories, foot-floor reaction forces, and anthropometric measurements were used with Vaughn's three dimensional inverse dynamics model [43] to determine the ankle angle and torque parameters. This model uses a 3-segment approximation of the lower limb (foot, shank, and thigh) and is based on the Newton-Euler equations. Ankle plantarflexion (PF)/dorsiflexion (DF) angle was extracted for three distinct times (disturbance onset, liftoff, and landing) and for two stages of the first step in the response: stage one was defined as disturbance onset to liftoff and stage two was defined as liftoff to landing. Ankle angle at liftoff and landing was calculated relative to the initial configuration (mean of the ankle angle during a one

second window just prior to disturbance onset). Within each stage, the maximum PF angle and DF angle were calculated relative to the angle at the beginning of the stage.

Within each stage the peak PF and peak DF torques were calculated relative to the values at the beginning of the stage. The peak vertical landing force was calculated as the maximum vertical force after landing and was scaled to body weight.

COP Parameters. The whole-body center of pressure (COP) was analyzed from disturbance onset time to landing time of the first step. The anterior-posterior (AP) and medial-lateral (ML) displacements of the COP relative to the location at disturbance onset were determined at liftoff and landing of the first step.

Statistical Analysis. Statistical analysis was done with SPSS 15.0 (SPSS Inc., Chicago, IL, USA). All three trials for each subject were used to evaluate group differences in strategy. A subject was defined as using a multiple step response if they used more than one step for any of the three trials. A subject was defined as being consistent in their choice of stepping limb if they used the same foot for all three trials. A p-value $\leq$ 0.05 was used to establish significant differences. A Fisher's two-tailed exact test was used to determine group differences in multiple vs. single step responses and consistency in choice of stepping limb. The Wilcoxon Rank Sum test was used to evaluate group differences in the number of steps utilized in the response.

Since the single step strategy may be fundamentally different from the multiple step strategy, only trials in which a multiple step strategy was utilized were included in the remaining analysis (temporal, kinematics, kinetics, COP). Preliminary results did show that a few parameters were statistically different between the multiple and single step strategy, confirming our assumption. Elimination of single step trials left 8 participants in each group, most of whom had at least 2 trials where they utilized a multiple step strategy. An additional HC and PD subject were not included in the ankle angle and torque calculations because of data collection problems with the Vicon markers.

Results from trials utilizing a multiple step response within a subject were averaged across the repeated trials and analyzed by separate MANOVAs for temporal (reaction time, weight shift time, step duration), kinematic (step length, step height, ankle angle at liftoff and landing, stage one and two max PF and max DF), kinetic (stage one and two peak PF and DF torque, peak vertical force at landing), and center of pressure (AP and ML position at liftoff and landing) sets of variables to determine the overall effect of group. Follow up t-tests were then done to investigate the individual parameters within each set that were the most sensitive to the presence of PD. Corrections for type 1 error were not done due to the fact that this is an exploratory study looking for parameters that may be sensitive to postural instability in early PD. Future studies, with the appropriate power and focused on the most promising parameters as indicated by the results of this study, will be needed to confirm these findings.

An initial MANOVA on all subjects' anthropometric (weight and height), initial stance (stance width, COP position under each foot) and pull characteristics (peak, duration, impulse) revealed no group differences (p = .944) and will not be considered further.

Results

The backwards pull consistently resulted in stepping responses in the HC and PD participants. All subjects regained his/her balance by taking between one and four steps.

Strategy. To evaluate differences in the step strategy variables, all trials from all subjects were evaluated. The average number of steps and the percentage of trials resulting in a multiple stepping strategy were remarkably similar between HC and PD (number of steps: 1.75 (.57) vs. 1.77 (.59); p=.940, percentage of multiple stepping trials: 90% vs. 80%; p >.999). However, only 50% of the PD participants were consistent in their choice of limb used for the first step, compared to 80% of the HC participants. Fisher's two-tailed exact test did not reveal a significant difference (p = .350). Only trials resulting in a multiple step strategy were used in the rest of the analysis.

Temporal. A MANOVA on the dependent temporal variables did not reveal a significant main effect of group (p = .092). In the follow up tests, the only temporal

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variable that showed a significant group difference was weight shift time (HC: 222 ms; PD: 500 ms; p = .023). Reaction time was similar between groups, and step duration time was longer in PD but not to a significant level.

Kinematics. A MANOVA on the dependent kinematic variables did not reveal a significant main effect of group (p = .280). In the follow up tests, the first stage ankle angle parameters showed significant group differences (liftoff angle (p = .016), max PF (p = .019), and max DF (p = .004)). During the first stage, the two groups showed a different trend in ankle motion. For example, the HC tended to go into plantarflexion (PF) immediately after disturbance onset and then rotated into dorsiflexion (DF) prior to liftoff, whereas the PD tended to go directly into DF. Therefore, at liftoff, the PD were in DF, whereas the HC were in PF (HC: 1.51 (3.84); PD: -4.10 (3.64); p = .016). At landing, PD were in more DF than HC (HC: -1.27 (3.91); PD: -5.09 (5.24); p = .148), but not to a significant level. The PD group had larger peak DF angles (HC: -.866 (1.32); PD: -4.89 (2.66); p = .004) and smaller peak PF angles (HC: 4.10 (1.66); PD: 1.68 (1.67); p = .019) during the onset of disturbance to liftoff stage. Motion during the liftoff to landing stage was similar between groups. The length and height of the first step were also similar between groups.

Kinetics. A MANOVA on the kinetic dependent variables did not reveal a significant main effect of group (p = 0.571). In the follow up tests, none of the individual variables showed significant group differences.

COP. A MANOVA on the COP dependent variables did not reveal a significant main effect of group (P = 0.228). In the follow up tests, the COP AP position at landing showed a difference between groups. The COP moved further posterior between disturbance onset to landing time in PD compared to HC (HC: 42 mm; PD: 71 mm; p = .032).

Discussion

This was an exploratory study designed to determine which parameters of balance recovery justify further investigation in the search for early markers of postural instability. MANOVAs were performed on four different sets of variables to conservatively investigate group differences, and then used follow up t-tests to investigate the sensitivity of individual parameters, even if the MANOVA result did not indicate a significant group difference. A focused follow-up study with appropriate statistical power must be designed to confirm these findings. The goal of this study was to identify the parameters that warrant further investigation. Thus, we will focus on the most sensitive findings, keeping the limitations of the approach in mind.

We found that even early in the progression of PD, prior to any clinical diagnosis of postural instability, a few differences in the response to a backwards pull are present. This change in response seems to be most reflected in the initial movement preparation phase for the first step taken in the multiple step strategy.

Strategy. Parkinson's disease did not affect the utilization of a single step response compared to a multiple step response. This may be a result of the magnitude of the disturbance used in this study. Even so, the PD subjects, compared to the HC, were less consistent in using the same foot for the initial step in the multiple step strategy. This result is consistent with the study by Jacobs *et al*. who showed that healthy subjects tend to step consistently with the same foot [28].

Temporal. PD did not affect the reaction time or the duration of the first step. Previous studies have shown that PD does not affect the reaction time after an external perturbation [20, 30, 44]. In the present study, PD did increase the weight shift time, which is the time between muscle activity onset and step foot liftoff. The inconsistent choice of the foot used for the initial step together with the longer weight shift time in the PD, compared to the HC, may be demonstrating what Jacobs *et al*. reported when healthy subjects were unable to pre-select their stepping foot: they had several anticipatory postural adjustments, leading to longer liftoff times compared to the condition where they were allowed to choose their stepping foot [28].

Kinematics. PD did affect the kinematics of the first step used in the response, but only prior to liftoff of that step. Both the ankle motion prior to liftoff and the ankle configuration at liftoff demonstrated group differences. The fact that the HC group

was in plantarflexion at liftoff is consistent with the results reported by Luchies *et al*. [34].

Kinetics. PD did not affect the torque generated at the ankle in response to the backwards pull. This is consistent with a study by Maki *et al*. [45] who investigated sit-to-stand in PD. They also showed similar magnitudes of ankle torque compared to healthy controls, but did see differences in the time to peak torque, which was not investigated here.

COP. The center of pressure differences observed indicate that the PD moved further posterior than the HC prior to landing. It is also clear that the AP movement of the COP is where the group differences are most likely going to be found, as the ML movements were very similar in the two groups.

Conclusions. Several differences in the response to a backwards pull were found in a PD population that has yet to clinically demonstrate balance impairments or postural instability. Most of the differences between the two groups were found in the movement preparation phase of the response (i.e. prior to liftoff of the first step). The weight shift, ankle kinematics, and center of pressure are important areas to investigate further. These results suggest that further investigation focused on the movement preparation stage may be able to identify early markers of postural instability. Further study is also necessary to determine the relationship between these

parameters and clinically defined postural instability. It will also be necessary to develop clinic-based tests that can be used to monitor those parameters that are sensitive enough to detect the postural instability in the early stages of PD.

Limitations. This study has limitations. For one, there was a small sample size and large number of parameters tested. As mentioned above, further studies with a more focused approach and appropriate statistical power are necessary to validate these findings. Another limitation of the study is that the same number of trials was not used for every subject (i.e. only trials that involved multiple steps were included). Further studies should be consistent in the number of trials used in the analysis. Finally, the subject population demonstrated a wide range of ages (48-77), UPDRS scores (10-60), and disease duration (1-13 years), and the effects of these conditions on the response parameters were not investigated. Further studies should investigate whether or not these conditions affect balance parameters.

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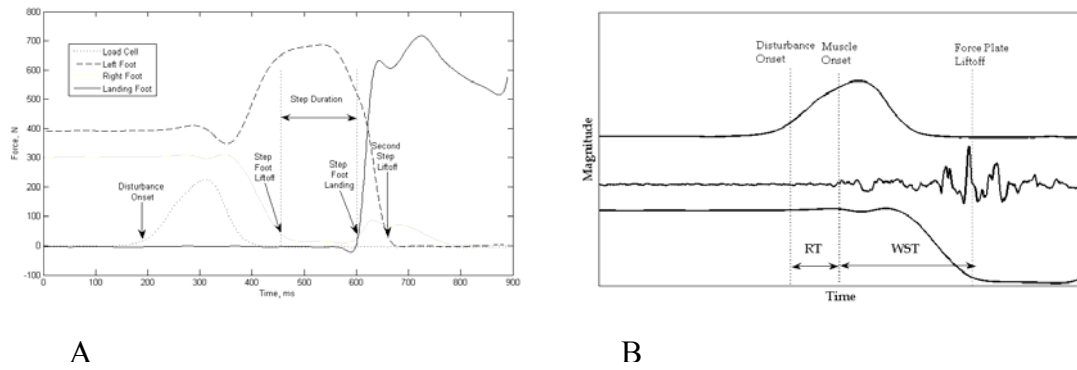
A   B

Figure 1. Illustration of temporal parameters. (A) Vertical forces from the left, right, and back force plate illustrating liftoff, landing, second liftoff, and step duration. (B) Top trace is load cell normal force, middle trace is TA EMG, bottom trace is step foot vertical force illustrating reaction time and weight
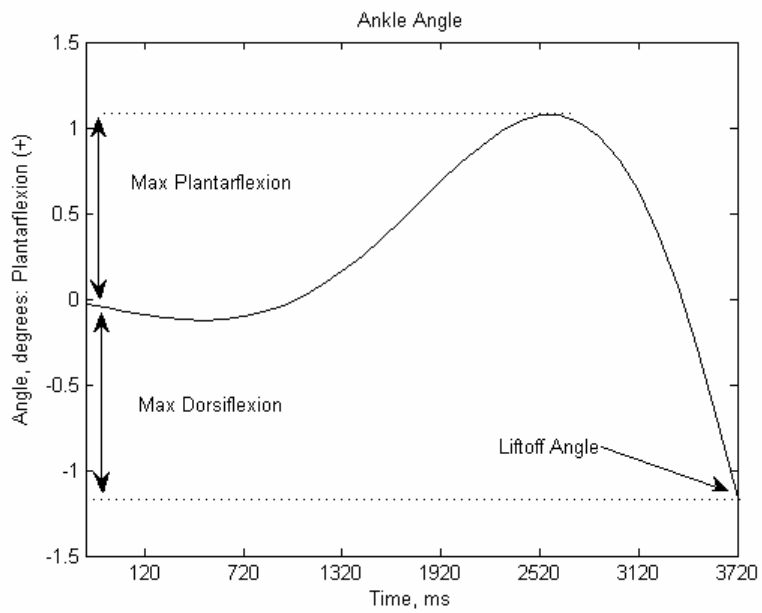
Figure 2. Demonstration of ankle angle parameters. Graph is a representative healthy subject from disturbance onset to liftoff.

Step Response Characteristics, HC vs. PD
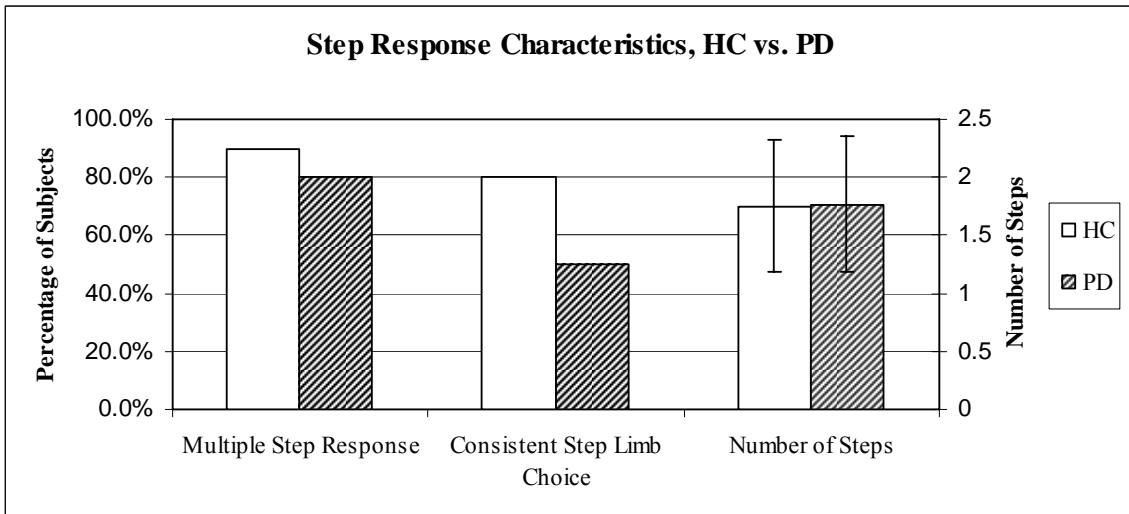
Figure 3. Strategy characteristics of step response. Left Axis: Multiple step response-more than one step was use in at least one trial; Consistent step limb choice- stepped with the same limb for all trials. Right Axis: Number of Steps- average number of steps in response.
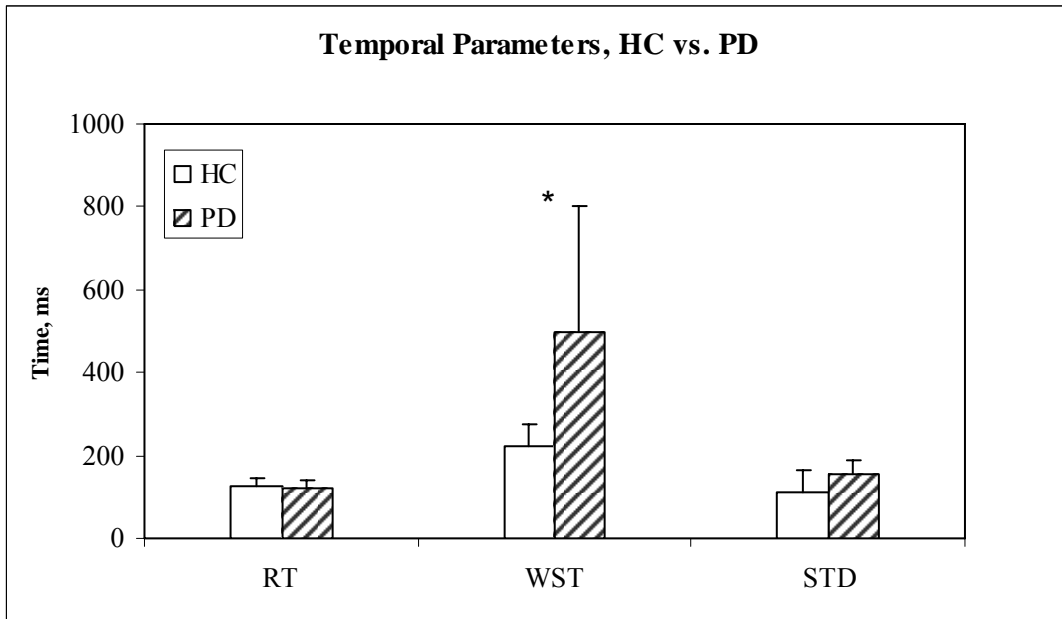
Figure 4. Temporal Parameters: RT (Reaction Time), WST (Weight Shift Time), STD (Step Duration Time).
* $p < .05$ in follow-up t-test
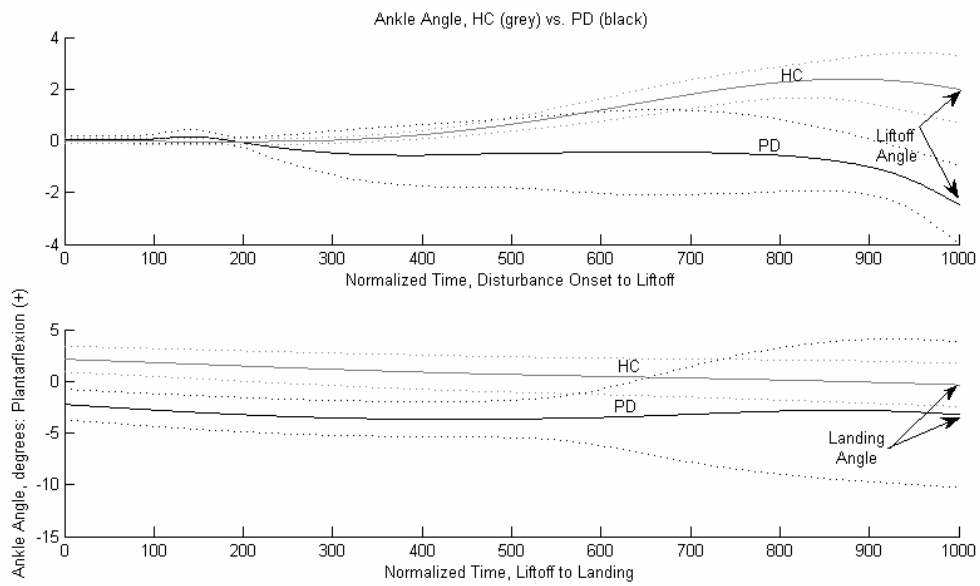
Figure 5. Group Average Ankle PF/DF Angle. Light trace is healthy, dark trace is PD. Top graph: disturbance onset to liftoff. Bottom graph: liftoff to landing. Solid lines are group averages, dotted lines are +/- 1 group standard deviation.
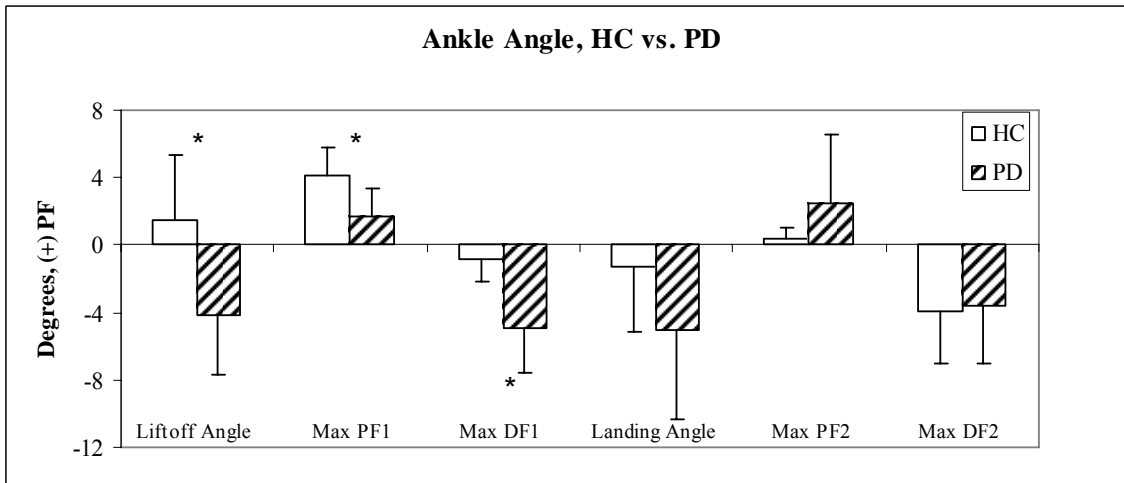
Figure 6. Ankle Angle Parameters. Positive is plantarflexion (PF), negative is dorsiflexion (DF). Liftoff and landing angles are relative to initial conditions. Max PF and DF in each stage are relative to angle at beginning of the stage. The number 1 indicates stage one (disturbance onset to liftoff) and 2 indicates stage two (liftoff to landing).
* $p < .05$ in follow-up t-test
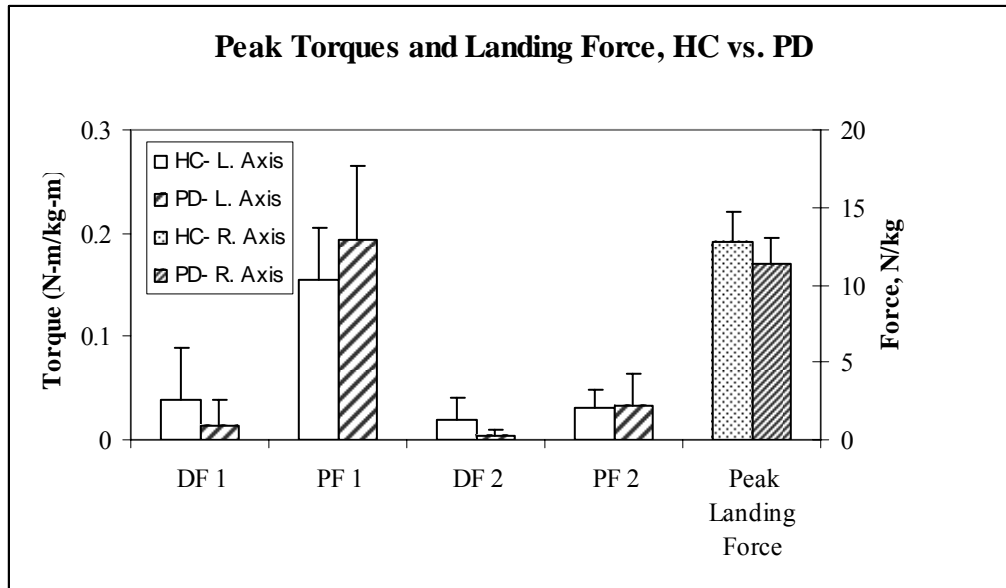
Figure 7. Kinetic parameters: Peak dorsiflexion (DF) and plantarflexion (PF) in stage one (disturbance onset to liftoff) and two (liftoff to landing), peak landing force. Torques are normalized to subject height times mass, landing force is normalized to subject mass.
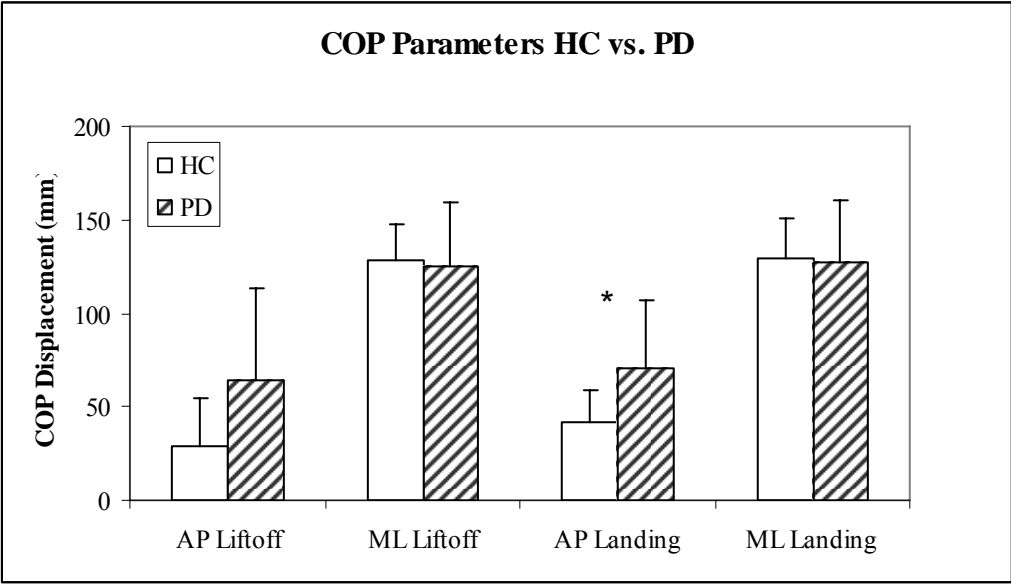
Figure 8. COP parameters: AP and ML location at liftoff and landing relative to location at disturbance onset.
* p<.05 in follow up t-test

Table 1. Characteristics of subject groups: mean +/- std. (range).

Subject Group	HC	PD
Age (years)	67 ± 11(48-79)	63 ± 9 (48-77)
Height (cm)	165 ± 11 (150-188)	167 ± 7 (158-176)
Mass (kg)	69 ± 11 (55-91)	76 ± 14 (55-94)
UPDRS-Motor	---	20 ± 9 (9-38)
UPDRS- Total	---	27 ± 15 (10-60)
UPDRS #33 (Pull Test)	---	0.22 ± 0.44 (0-1)

Table 2. Initial stance and pull characteristics: mean (std). P-values determined from follow-up t-tests.

	HC	PD	p-value
Mass (kg)	69 (11)	76(14)	.195
Height (cm)	165 (11)	167 (7)	.658
Stance Width (% height)	19 (3)	17 (6)	.425
COP Right Foot (% foot length)	27 (5)	27 (8)	.970
COP Left Foot (% foot length)	27 (3)	24 (16)	.558
Peak Force (N)	211 (22)	223 (29)	.296
Duration (ms)	275 (29)	267 (23)	.480
Impulse (N-ms)	22 (3)	23 (3)	.756

Table 3. Average temporal characteristics: mean (std).

	HC	PD	p-value
Reaction Time (ms)	124 (19)	123 (17)	.910
Weight Shift Time (ms)	222 (54)	500 (304)	.023*
Step Duration (ms)	113 (51)	153 (33)	.076

* p<.05 in follow-up t-test

Table 4. Average kinematic characteristics of the first step: mean (std). All angles are in degrees, step length and height are a percentage of subject height.

	HC	PD	p-value
Liftoff Angle	1.51 (3.84)	-4.10 (3.64)	.016*
Max PF S1	4.10 (1.66)	1.68 (1.67)	.019*
Max DF S1	0.866 (1.32)	4.89 (2.66)	.004*
Landing Angle	-1.27 (3.91)	-5.09 (5.24)	.148
Max PF S2	0.40 (0.642)	2.43 (4.10)	.221
Max DF S2	3.88 (3.15)	3.61 (3.44)	.879
Step Length	8.16 (3.66)	10.20 (4.56)	.375
Step Height	1.37 (1.95)	1.79 (2.51)	.733

* $p < .05$ in follow-up t-test

Table 5. Average kinetic characteristics of the first step: mean (std). All torques are normalized to body weight times height (N-m/kg-m); peak landing force is normalized by body weight (N/kg). P-values determined from follow-up t-tests.

	HC	PD	p-value
Peak DF Torque S1	0.039 (0.050)	0.013 (0.026)	.244
Peak PF Torque S1	0.154 (0.051)	0.194 (0.072)	.249
Peak DF Torque S2	0.019 (0.022)	0.004 (0.006)	.113
Peak PF Torque S2	0.031 (0.017)	0.033 (0.030)	.860
Peak Landing Force	12.80 (1.88)	11.36 (1.61)	.149

Table 6. Average center of pressure location at liftoff and landing of the first step: mean (std). All values are relative to the COP position at disturbance onset. Positive values represent backwards movement.

	HC	PD	p-value
COP AP-liftoff (mm)	29.29 (25.32)	63.99 (48.91)	.090
COP ML-liftoff (mm)	128.4 (19.15)	125.0 (33.88)	.669
COP AP-landing (mm)	42.06 (16.84)	70.71 (36.63)	.032*
COP ML-landing (mm)	129.0 (21.87)	127.2 (33.36)	.768

* p<.05 in follow-up t-test

CHAPTER FOUR: SUMMARY

Summary of Study

The goal of this study was to investigate parameters of balance recovery that may be sensitive to postural instability early in the progression of Parkinson's disease. Healthy control (HC) participants and participants with mild Parkinson's disease (PD) responded naturally to a backwards pull at the waist. Video, motion, EMG, force plate, and load cell data were used to quantify the response in terms of strategy, temporal, kinematic, kinetic, and center of pressure parameters. Strategy parameters included whether the participant used a single or multiple step response, the number of steps in the response, and whether or not they were consistent in the choice of stepping limb over multiple trials. Temporal parameters included reaction time, weight shift time, and step duration. Kinematic parameters included step length, step height, ankle angle at liftoff and landing, and peak ankle plantarflexion/ dorsiflexion angle. Kinetic parameters included peak plantarflexion/dorsiflexion ankle torque, and peak vertical force. Center of pressure parameters included COP position at liftoff and landing of the first step.

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A few parameters showed differences between the two groups. The PD group was less consistent in their choice of stepping limb, but did not take more steps or use

a multiple step strategy more frequently than the controls. The PD group had a longer weight shift time, although the reaction times and step duration times were similar. The PD group showed different motion at the ankle prior to liftoff and were in dorsiflexion at liftoff whereas the HC were in plantarflexion. They did not show different ankle motion after liftoff. There were no group differences in peak torques or peak landing force; however the center of pressure was further posterior at landing in the PD, compared to the HC group.

Conclusions and Recommendations

This study found differences in the initial response to the backwards pull between healthy controls and the participants with Parkinson's disease. The PD group, compared to the HC group, were less consistent in the choice of stepping limb, had a longer weight shift time, and showed a different motion at the ankle joint prior to liftoff. Most of the differences between the two groups were found in the movement preparation phase of the response (i.e. prior to liftoff of the first step). These results suggest that further investigation focused on the movement preparation stage may be able to identify early markers of postural instability. Further study is also necessary to determine the relationship between these parameters and clinically defined postural instability. It will also be necessary to develop clinical tests that can be used to monitor those parameters that are sensitive enough to detect the postural instability in the early stages of PD.

Study Limitations

This study has limitations. For one, there was a small sample size and large number of parameters tested. Since this study was designed to provide insights into where to look next, further studies with a more focused approach are necessary to validate these findings. Another limitation of the study is that the same number of trials was not used for every subject- only trials that involved multiple steps were included and average performance across the trials was analyzed. Further studies should be consistent in the number of trials. Finally, the subject population in this study had a wide age range, UPDRS score, and disease duration, but the effects of these conditions were not investigated. Future studies should determine the effects of these conditions on each group.

Further Study

This study investigated a wide range of balance recovery parameters and found significant differences in a few of the parameters, almost all of which were in the initial movement preparation phase for the first step. The next step is to validate these findings in a more focused study with appropriate statistical power (estimated by preliminary power analysis to be 17 in each group based on an effect size of 0.8). Next, it is important to further dissect the initial stage of response. Future studies should look at the COP and anticipatory postural adjustments during the initial stage as well. Finally, these parameters should be investigated for sensitivity and specificity

to postural instability and fall risk by testing subjects in further stages of the disease

and with a history of falls.

APPENDIX A: EXPERIMENTAL PROTOCOL

Date of Screen:

Subject name: _____
                  Last   First

"My name is _____. I am calling from the Center on Aging at KU Medical Center. I was given your name as someone who had indicated an interest in participating in a research study. We are now beginning a study looking at how the brain controls our balance and how that might be related to risk of falling. If you think you might be interested in participating, and you have a few minutes, I'd like to describe the study to you."

Is subject interested?   YES   NO
        Comments:_____

If NO: "Thank you for your time. Would you be interested in being contacted for future studies or do you prefer that your name is removed from our list?"
        Comments:_____

If YES: "Please feel free to ask questions at any time. This study is a two-part evaluation that will look at how Parkinson's disease affects the ability of the brain to control our balance. We will be looking at those with Parkinson's compared to healthy adults in the same age range. The first part of the study is a medical screen that we will do over the phone. The phone call will take approximately 40 minutes and will include questions about current and previous health conditions. The final part of the study includes a visit to the Human Performance Laboratory in the Center on Aging where we will do a physical assessment and ask you to do four different tests including standing still while we record the natural sway of your body, starting to walk from rest, walking on a treadmill, and a balance recovery test. During all of the tests, you will be wearing a protective harness to ensure your safety. The final part of the test will take approximately 3 hours. There is no cost for participating in this study, nor are there any direct benefits to you. Do you think you might be interested in participating?

Interested?
Notes:

This study will be done at the Landon Center on Aging at KU Medical Center. Would you have transportation to and from the KU Medical Center for this one visit?

What is your age and date of birth?

_____

If you are interested in participating, I will have a research associate contact you to review your health history and schedule a time for you to visit the laboratory. This phone call will take approximately 30-40 minutes. Is there a day/time that is convenient for you?
_____
Thank you.

***Please give this sheet to Molly McVey who will make the next phone call. Thanks. ***

Subject Identification Number:
Date of Screen:

Subject name: _____

                       Last   First

"My name is _____. I am calling from the Center on Aging at KU Medical Center. I was given your name as someone who had indicated an interest in participating in a research study. We are now beginning a study looking at how the brain controls our balance and how that might be related to risk of falling. If you think you might be interested in participating, and you have a few minutes, I'd like to describe the study to you."

Is subject interested?   YES   NO
        Comments:_____
        _____

If NO: "Thank you for your time. Would you be interested in being contacted for future studies or do you prefer that your name is removed from our list?"
        Comments:_____
        _____

If YES: "Please feel free to ask questions at any time. This study is a one-time evaluation that will look at how Parkinson's disease affects the ability of the brain to control our balance. We will be looking at those with Parkinson's compared to healthy adults in the same age range. There are two parts to this study. First, there is a medical screening procedure. The first part is done over the phone and will take approximately 20 minutes. This will include questions about current and previous health conditions. Once that is completed we will schedule you for a visit to the Human Performance Lab in the Center on Aging where we will do a physical assessment that and then do the balance testing. For the balance testing, we will ask you to do four different tests including standing still, starting to walk from rest, walking on a treadmill, and a balance recovery test. For the balance recovery test, we will pull you backwards from the waist and you will have to regain your balance. During all of the tests, you will be wearing a protective harness to ensure your safety. The whole test will take approximately 3 hours. There is no cost for participating in this study, nor are there any direct benefits to you. If you are still interested, I would like to ask you some questions to see if you would be able to participate in this study."

Notes:_____
_____

**If subject is excluded by any questions, stop the interview and explain to the subject the reason for exclusion. Thank them for their time and willingness to participate.

Name: _____ Age:_____

Birthdate:_____

Gender: M   F

Address: _____

Phone: _____

Schooling/Occupation: _____

Height: _____Weight: _____

Are you currently participating in any other research studies?

This study will require one trip to the Landon Center on Aging at KU Medical Center. Would you have transportation to and from the KU Medical Center for these two visits?

Are you able to get out of bed and also use the bathroom without assistance from anything or anyone?

Are you able to stand on your own for 10 minutes without assistance?
(ex. Can you stand at the bathroom sink to do your morning care without having to hold to something?)

SUMMARY OF MEDICAL SCREEN:

Pass? If no, why not?   Height: _____ Weight:_____ Age:_____ Gender: _____   Comments:

Have you been diagnosed with:	Yes	No	When	Details	Exclude?
Ever had major surgery or amputation?					Yes if affects legs, not recovered completely
Osteoporosis					Yes
Brittle Bones					Yes
Fibromyalgia? Constant aches and fatigue?					Yes if constant
Arthritis					Yes if in legs
Nerve Damage					Yes if in legs
Heart Attack					Yes
Heart Disease or problems (surgeries, valve replacement, angina, pacemaker?)					Yes
Chest Pain from heart disease?					Yes
Polio or Post Polio Syndrome					Yes
Broken Bones? Compression fractures?					Yes if < 2 years ago and in leg or spine
Ever had a hip, knee, or ankle replacement or surgery?					Yes
Ever had a joint fusion?					Yes
Diabetes? Thyroid conditions?					Yes if not controlled or if have neuropathy
High Blood Pressure					Yes if not controlled on meds
Neurological Disease (MS, ALS, Dementia, Seizure disorders, PD)					Yes
Stroke or TIA					Yes
Cancer, Leukemia, Lymphoma?					Yes if currently being treated
Anemia					Yes if has had blood transfusion in last year
Seizure					Yes
Meniere's Disease? Inner Ear Damage? Vertigo? Ear infection right now?					Yes

Acoustic Neuroma? Tinnitus? (ringing, buzzing in ears) Do you feel pressure in ears?					Yes if constant
Do you have any problems with:	**Yes**	**No**	**How does it affect ADL?**		**Exclude?**
Pain or stiffness in hips? Knee? Ankles? Back? Shoulder?					Yes if affects walking, standing
Hip, Knee, or Ankle injury?					Yes if affects walking, standing
Back Problems? If yes: • What motions cause pain (bending, twisting, lifting, quick movements?) • How irritable is the pain? • How do you treat the pain? • Have you seen a doctor?					Yes if brought on by walking, standing, quick movements, if brought on easily
Muscle Problems in leg? Weakness in legs? Does it limit how far you can walk or how long you can stand?					Yes if affects walking, standing
Poor circulation in legs causing them to become cold, numb, or causes cramping while walking, been diagnosed with PVD? Claudication?					Only if causes problems when walking or standing
Lung disease? Emphezema? Chronic Bronchitis? SOB? DOE?					Yes if affects walking, standing
Ever had a head or neck injury?					Not necessarily
Gout or Psuedogout?					Not necessarily
Foot problems?					Not necessarily
Hearing Problems? Hearing aid? Last hearing exam?					Not necessarily
Have you been hospitalized in the past year? Major illness in last year?					Not necessarily

Headaches				Not necessarily
Neuropathy				Not necessarily
Vision				Not necessarily
Falls				Not necessarily
Driving				Not necessarily
Night Driving				Not necessarily
Shortness of Breath				Not necessarily
Edema (swelling of legs)				Not necessarily
Fainting or lightheadedness?				Not necessarily
Memory				Not necessarily
Burning pain or weakness anywhere in body?				Not necessarily
Depression				Not necessarily

MEDICATIONS:

What medications are you currently taking?

Name: _____ Amt _____ Time_____

Name: _____ Amt _____ Time_____

Name: _____ Amt _____ Time_____

Name: _____ Amt _____ Time_____

Name: _____ Amt _____ Time_____

Name: _____ Amt _____ Time_____

Name: _____ Amt _____ Time_____

OTC Medications:

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 _____

When you transfer from a sitting to standing position, do you do it:

Alone   With assistive device   With person assist   Unable

When you transfer from lying down to sitting, do you do it:

Alone   With assistive device   With person assist   Unable

Hand dominance   L   R   Leg dominance L   R

(Are you right or left-handed?)   (Which leg would you kick a ball with?)

Recent vision screen? If yes, when?

BARTHEL INDEX: SEE FULL VERSION

	Independent	With Help
1. Feeding	5	10
2. Moving from wheelchair to bed and return	5-10	15
3. Personal toilet (wash face, comb hair, etc.)	0	5
4. Getting on and off toilet (handling clothes, flush, wipe)	5	10
5. Bathing self	0	5
6. Walking on level surface	10	15
7. Ascend and descend stairs	5	10
8. Dressing (includes tying shoes, fastening)	5	10
9. Controlling bowels	5	10
10. Controlling bladder	5	10

Is there anything else you can think of about your current or past health state that we might need to know?

"With these initial questions it appears that you are eligible for the next step in the study. The next step involves a physical evaluation by a physical therapist and geriatrician here at the Center on Aging. The evaluation will take approximately one hour. We are now scheduling participants for _____. Would you be able to come to the Center on Aging to participate during this time?"

If NO: "We will be continuing to test more participants in the coming weeks and months. Can we contact you to schedule a time in future?"

"We like to schedule to start in the morning or after lunch around 1:00…..*schedule a time with them.

Is participant interested?
        a. Visit scheduled _____
        b. Visit delayed (specify reason)_____
        c. Subject requests delay and reinquiry at a later date: _____
        d. Subject and/or family expresses wish for no further contact.

Notes:

Subject Identification Number:

Date of Screen:

Subject name: _____

              Last   First

"My name is _____. I am calling from the Center on Aging at KU Medical Center. I was given your name by Dr. Lyons and Dr. Pahwa in the Parkinson's Disease Center at KUMC as someone who had indicated an interest in participating in a research study. We are now beginning a study looking at how Parkinson's disease affects the ability of the brain to control our balance and how that might be related to risk of falling. If you think you might be interested in participating, and you have a few minutes, I'd like to describe the study to you."

Is subject interested?   YES   NO
        Comments:_____

_____

If NO: "Thank you for your time. Would you be interested in being contacted for future studies or do you prefer that your name is removed from our list?"
        Comments:_____

_____

If YES: "Please feel free to ask questions at any time. This study is a one time evaluation that will look at how Parkinson's disease affects the ability of the brain to control our balance. We will have you do four different tests including standing still, starting to walk from rest, walking on a treadmill, and a balance recovery test. For the balance recovery test, we will pull you backwards from the waist and you will have to regain your balance. During all of the tests, you will be wearing a protective harness to ensure your safety. Either before or after the balance testing, Dr. Lyons will do a clinical evaluation that will take approximately 15-30 minutes. The whole session will take about 2.5-3 hours. There is no cost for participating in this study, nor are there any direct benefits to you. If you are still interested, I would like to ask you some questions to see if you would be able to participate in this study." Next, I will be asking about your previous and current health and this phone call will take approximately 30 minutes. Are you still interested?

Notes:_____

_____

**If subject is excluded by any questions, stop the interview and explain to the subject the reason for exclusion. Thank them for their time and willingness to participate.

Name: _____ Age:_____

Birthdate:_____

Gender: M   F

Address: _____

Phone: _____

Schooling/Occupation: _____

Height: _____Weight: _____

Are you currently participating in any other research studies?

This study will be done at the Landon Center on Aging at KU Medical Center. Would you have transportation to and from the KU Medical Center for this one visit?

Are you able to get out of bed and also use the bathroom without assistance from anything or anyone?

Are you able to stand on your own for 10 minutes without assistance?
(ex. Can you stand at the bathroom sink to do your morning care without having to hold to something?)

SUMMARY OF MEDICAL SCREEN:

<table>
<tr><td>

Pass? If no, why not?

Height: _____ Weight:_____Age:_____Gender: _____

Comments:

</td></tr>
</table>

Have you been diagnosed with:	Yes	No	When	Details	Exclude?
Ever had major surgery or amputation?					Yes if affects legs, not recovered completely
Osteoporosis					Yes
Brittle Bones					Yes
Fibromyalgia? Constant aches and fatigue?					Yes if constant
Arthritis					Yes if in legs
Nerve Damage					Yes if in legs
Heart Attack					Yes
Heart Disease or problems (surgeries, valve replacement, angina, pacemaker?)					Yes
Chest Pain from heart disease?					Yes
Polio or Post Polio Syndrome					Yes
Broken Bones? Compression fractures?					Yes if < 2 years ago and in leg or spine
Ever had a hip, knee, or ankle replacement or surgery?					Yes
Ever had a joint fusion?					Yes
Diabetes? Thyroid conditions?					Yes if not controlled or if have neuropathy
High Blood Pressure					Yes if not controlled on meds
Neurological Disease (MS, ALS, Dementia, Seizure disorders, PD)					Yes
Stroke or TIA					Yes
Cancer, Leukemia, Lymphoma?					Yes if currently being treated
Anemia					Yes if has had blood transfusion in last year
Seizure					Yes
Meniere's Disease? Inner Ear Damage?					Yes

Vertigo? Ear infection right now?				
Acoustic Neuroma? Tinnitus? (ringing, buzzing in ears) Do you feel pressure in ears?				Yes if constant

Do you have any problems with:	**Yes**	**No**	**How does it affect ADL?**	**Exclude?**
Pain or stiffness in hips? Knee? Ankles? Back? Shoulder?				Yes if affects walking, standing
Hip, Knee, or Ankle injury?				Yes if affects walking, standing
Back Problems? If yes: • What motions cause pain (bending, twisting, lifting, quick movements?) • How irritable is the pain? • How do you treat the pain? • Have you seen a doctor?				Yes if brought on by walking, standing, quick movements, if brought on quickly
Muscle Problems in leg? Weakness in legs? Does it limit how far you can walk or how long you can stand?				Yes if affects walking, standing
Poor circulation in legs causing them to become cold, numb, or causes cramping while walking, been diagnosed with PVD? Claudication?				Only if causes problems when walking or standing
Lung disease? Emphezema? Chronic Bronchitis? SOB? DOE?				Yes if affects walking, standing
Ever had a head or neck injury?				Not necessarily

Gout or Psuedogout?				Not necessarily
Foot problems?				Not necessarily
Hearing Problems? Hearing aid? Last hearing exam?				Not necessarily
Have you been hospitalized in the past year? Major illness in last year?				Not necessarily
Headaches				Not necessarily
Neuropathy				Not necessarily
Vision				Not necessarily
Falls				Not necessarily
Driving				Not necessarily
Night Driving				Not necessarily
Shortness of Breath				Not necessarily
Edema (swelling of legs)				Not necessarily
Fainting or lightheadedness?				Not necessarily
Memory				Not necessarily
Burning pain or weakness anywhere in body?				Not necessarily
Depression				Not necessarily

MEDICATIONS:
What medications are you currently taking?
Name: _____ Amt _____ Time _____
Name: _____ Amt _____ Time _____
Name: _____ Amt _____ Time _____
Name: _____ Amt _____ Time _____
Name: _____ Amt _____ Time _____
Name: _____ Amt _____ Time _____
Name: _____ Amt _____ Time _____
**Testing should occur 1-2 hours after last dose of medication.

OTC Medications:

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 _____

When you transfer from a sitting to standing position, do you do it:
Alone   With assistive device   With person assist   Unable

When you transfer from lying down to sitting, do you do it:
Alone   With assistive device   With person assist   Unable

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

Recent vision screen? If yes, when?

Is there anything else you can think of about your current or past health state that we might need to know?

When were you first diagnosed with Parkinson's disease?

What was the first symptom you experienced? When did you experience the first symptom?

Are you affected on one or both sides of your body? Which side is more affected?

Do you feel like you have bad balance? Do you have difficulty maintaining your balance while: standing still, walking, changing positions?

Have you fallen in the past year?
Event: _____Date:_____Injury:_____
Circumstances: _____
Event: _____Date:_____Injury:_____
Circumstances: _____
Event: _____Date:_____Injury:_____
Circumstances: _____

How often do you fall?

Do you currently use any devices to assist you (canes, walker, etc?)

 "With these initial questions it appears that you are eligible for this study. We are now scheduling participants for _____. Would you be able to come to the Center on Aging to participant during this time?"

If NO: "We will be continuing to test more participants in the coming weeks and months. Can we contact you to schedule a time in future?"

"We like to schedule to start in the morning or after lunch around 1:00…..*schedule a time with them.

Is participant interested?
        a. Visit scheduled _____
        b. Visit delayed (specify reason)_____
        c. Subject requests delay and reinquiry at a later date: _____
        d. Subject and/or family expresses wish for no further contact.

Notes:

Dear _____,

Thank you for agreeing to participate in our research study!

Your appointment is scheduled for _____**.** and will be about 3 hours long.

This study looking at how Parkinson's disease affects balance will be conducted in the Human Performance Lab, which is located on the first floor of the Landon Center on Aging at KU Medical Center. Parking is located in front of the building. A map is included with this letter to help you locate us.

When you arrive at the Center on Aging, **please have a seat in the main waiting area on the first floor.** A research associate will be out shortly to greet you and bring you to the testing area.

Please note that this study is not being conducted through the Parkinson's Disease Center or the Neurology Clinic. Therefore, they will not have a record of your appointment. If you have any questions or need to reschedule your appointment, please contact **Molly McVey** at **785-218-2714**.

Thank you,

Molly McVey
Graduate Research Assistant
Human Performance Lab
Center on Aging, KUMC

PHYSICAL EXAMINATION DATA

Height   **Weight**

Sitting BP-P

Supine BP-P   Standing BP-P

Strength	*Left*	*Right*		*Left*	*Right*
Shld Abd			Hip Ext		
Biceps			Hip Abd		
Triceps			Hip Add		
Wst Flex			Knee Ext		
Wst Ext			Knee Flex		
Grip			Ankle Df		
Hip Flex			Ankle Pf		

Reflexes		Patellar	
Biceps		Achilles	
Triceps		Babinski	

Sensory	Position		Vibration		Pin Prick	
	Left	*Right*	*Left*	*Right*	*Left*	*Right*
Upp Ext						
Low Ext						

Cerebellar	*Left*	*Right*
Fing-Nose		
Heel-Shin		

Cardiac

Pulm

Ears

Gross Cranial Nerves	*Left*	*Right*	(Other)	*Left*	*Right*
EOM					
Facial					

Tone	*Left*	*Right*
Cogwheeling		

Station and Gait

Romberg

Gait

Musculoskeletal deformities and contractures

Joint/Extremity (pain ROM)

Lymphatic

Back

Neuro	Tremor
	Rigidity
	Dyskinesia
	Spasticity

Other/comments

BARTHEL INDEX

INSTRUCTIONS: The Barthel Index is a record of what a <u>patient does</u> **not** a record of what a patient could do. Full credit is not given for an activity if the patient needs even minimal help/supervision. A score of (0) is given when a patient cannot meet the criteria as defined. Circle the appropriate answer to each question.

1.   Today, are you able to feed yourself?

    10:    Independent; feeds self from tray or table; can put on assistive device if needed; accomplishes feeding in reasonable time.
    5:    Assistance necessary with cutting food, etc.
    0:    Cannot meet criteria
    88:    Contraindicated due to _____

2.   Today, are you able to get out of bed or into a chair?

    15:    Independent in all phases of this activity
    10:    Minimal help needed or patient needs to be reminded or supervised for safety of one or more parts of this activity.
    5:    Patient can come to sitting position without help of second person, but needs to be lifted out of bed and assisted with transfers
    0:    Cannot meet criteria
    88:    Contraindicated due to _____

3.   Today, are you able to wash your face, brush your teeth, brush your hair, etc.?

    5:    Can wash hands, face; combs hair, cleans teeth. Can shave (males) or apply makeup (females) without assistance; females need not braid or style hair.
    0:    Cannot meet criteria
    88:    Contraindicated due to_____

4.   Today are you able to get on and off the toilet?

    10:    Able to get on and off the toilet, fastens/unfastens clothes; can use toilet paper without assistance. May use wall bar or other support if needed; if bedpan is necessary, patient can place it on chair, empty, and clean it.
    5:    Needs help because of imbalance or other problems with clothes or toilet paper
    0:    Cannot meet criteria
    88:    Contraindicated due to _____

5.   Today, are you able to bathe yourself?

5:     May use tub, shower, or sponge bath. Patient must be able to perform all functions without another person being present.
0:     Cannot meet criteria
88:    Contraindicated due to _____

6.   Today, are you able to walk without help?

15:    Patient can walk at least 50 yards without assistance or supervision; may use braces, prostheses, crutches, canes, or walker, but not a rolling walker. Must be able to lock/unlock braces, assume standing or seated position, get mechanical aids into position for use and dispose of the mechanical aids when seated (putting on and off braces should be scored under dressing).
10:    Assistance needed to perform above activities, but can walk 50 yards with little help.
0:     Cannot meet criteria
88:    Contraindicated due to _____

7.   Today, are you able to use a wheelchair? (Do not score if patient competes score for walking- item #6).

5:     Patient cannot ambulate, but can propel wheelchair independently; can go around corners, turn around and maneuver chair to table, bed, toilet, etc; must be able to push chair 50 yards.
0:     Cannot meet criteria
88:    Contraindicated due to_____

8.   Today, are you able to walk up and down stairs?

10:    Able to go up and down flights of stairs safely without supervision; using canes, handrails, or crutches when needed and can carry these items as ascending/descending.
5:     Needs help or supervision of any of the above items.
0:     Cannot meet criteria
88:    Contraindicated due to _____

9.   Today, are you able to dress and undress yourself?

10:    Able to put on, fasten, and remove all clothing; ties shoelaces unless necessary adaptations used. Activity includes fastening braces and corsets when prescribed; suspenders, loafer shoes, and dresses opening in the front may be used when necessary.
5:     Needs help putting on, fastening, or removing clothing; must accomplish at least half of task alone within reasonable time; women need not be scored on use of brassiere or girdle undless prescribed.
0:     Cannot meet criteria
88:    Contraindicated due to _____

10.   Today, are you able to control your bowels?

10: Able to control bowels and have no accidents. Can use a suppository or take an enema when necessary (as for spinal cord injury patients who have had bowel training).

5: Needs help in using a suppository or taking an enema or has occasional accidents.

0: Cannot meet criteria

88: Contraindicated due to _____

11. Today, are you able to control your bladder?

10: Able to control bladder day and night. Spinal injury patients must be able to put on external devices and leg bags independently, clean and empty bag, and must stay dry day and night.

5: Occasional accidents occur, cannot wait for bedpan, does not get to toilet in time or needs help with external device.

0: Cannot meet criteria

88: Contraindicated due to _____

12. Information for today's Barthel data gathered from:
   01: Patient
   02: Proxy- Caregiver
   03: Proxy- Other
   04: Chart
   05: Both patient and proxy

Environmental Assessment:

1. Do you live in a home, apartment, or assisted living facility?

2. Do you have stairs in your home? How often do you use them?

Staircase #1: _____ Frequency: _____
Staircase #2: _____ Frequency: _____
Staircase #3: _____ Frequency: _____
Staircase #4: _____ Frequency: _____

3. Do you live alone? With a spouse or partner? Do you have a caretaker (live-in or otherwise)?

4. Do you use any type of assistive devices at any time during a normal day? (Walkers, canes, etc?)

5. Do you ever use assistance from someone else during a normal day? (Taking a hand to go down steps, get out of a car, etc.)?

6. Have you ever modified anything in your home to reduce the risk of falling? When?

Modification: _____ Date: _____
Modification: _____ Date: _____
Modification: _____ Date: _____
Modification: _____ Date: _____
Modification: _____ Date: _____

BINDING LINE

University of Kansas Medical Center
3901 Rainbow Boulevard   Kansas City, KS 66160
Department of Neurology

☐ Meds Off   ☐ Meds On

Patient Name _____

Med. Rec. No. _____

I.   MENTATION, BEHAVIOR AND MOOD

1. Intellectual Impairment ....

    0 = None
    1 = Mild. Consistent forgetfulness with partial recollection of events and no other difficulties
    2 = Moderate memory loss, with disorientation and moderate difficulty handling complex problems. Mild but definite impairment of function at home
        with need of occasional prompting.
    3 = Severe memory loss with disorientation for time and often to place. Severe impairment in handling problems.
    4 = Severe memory loss with orientation preserved to person only. Unable to make judgements or solve problems. Requires much help with personal
        care. Cannot be left alone at all.
    9 = Information Missing

2. Thought Disorder ....

    0 = None
    1 = Vivid dreaming.
    2 = "Benign" hallucinations with insight retained.
    3 = Occasional to frequent hallucinations or delusions; without insight; could interfere with daily activities.
    4 = Persistent hallucinations, delusions, or florid psychosis. Not able to care for self.
    9 = Information Missing

3. Depression ....

    0 = Not present
    1 = Periods of sadness or guilt greater than normal, never sustained for days or weeks.
    2 = Sustained depression (1 week or more).
    3 = Sustained depression with vegetative symptoms (insomnia, anorexia, weight loss, loss of interest).
    4 = Sustained depression with vegetative symptoms and suicidal thoughts or intent.
    9 = Information Missing

4. Motivation / Initiative ....

    0 = Normal
    1 = Less assertive than usual; more passive.
    2 = Loss of initiative or disinterest in elective (non-routine) activities.
    3 = Loss of initiative or disinterest in day-to-day (routine) activities.
    4 = Withdrawn, complete loss of motivation.
    9 = Information Missing

5. Total Mentation Score ....

II.   ACTIVITIES OF DAILY LIVING

6. Speech ....

    0 = Normal
    1 = Mildly affected. No difficulty being understood.
    2 = Moderately affected. Sometimes asked to repeat statements.
    3 = Severely affected. Frequently asked to repeat statements.
    4 = Unintelligible most of the time.
    9 = Information Missing

Date _____   **UPDRS**   Page 1 of 8

7. Salivation ...._____
      0 = Normal
      1 = Slight but definite excess of saliva in mouth; may have nighttime drooling.
      2 = Moderately excessive saliva; may have minimal drooling.
      3 = Marked excess of saliva with some drooling.
      4 = Marked drooling, requires constant tissue or handkerchief.
      9 = Information Missing

8. Swallowing ...._____
      0 = Normal
      1 = Rare choking.
      2 = Occasional choking.
      3 = Requires soft food.
      4 = Requires NG tube or gastrostomy feeding.
      9 = Information Missing

9. Handwriting ...._____
      0 = Normal
      1 = Slightly slow or small.
      2 = Moderately slow or small; all words are legible.
      3 = Severely affected; not all words are legible.
      4 =.The majority of words are not legible.
      9 = Information Missing

10. Cutting food and handling utensils ...._____
      0 = Normal
      1 = Somewhat slow and clumsy, but no help needed.
      2 = Can cut most foods, although clumsy and slow; some help needed.
      3 = Food must be cut by someone, but can still feed slowly.
      4 = Needs to be fed.
      9 = Information Missing

11. Dressing ...._____
      0 = Normal
      1 = Somewhat slow, but no help needed.
      2 = Occasional assistance with buttoning, getting arms in sleeves.
      3 = Considerable help required, but can do some things alone.
      4 = Helpless.
      9 = Information Missing

12. Hygiene ...._____
      0 = Normal
      1 = Somewhat slow, but no help needed.
      2 = Needs help to shower or bathe; or very slow in hygienic care.
      3 = Requires assistance for washing, brushing teeth, combing hair, going to bathroom.
      4 = Foley catheter or other mechanical aids.
      9 = Information Missing

13. Turning in bed and adjusting bed clothes ...._____
      0 = Normal
      1 = Somewhat slow and clumsy, but no help needed.
      2 = Can turn alone or adjust sheets, but with great difficulty.
      3 = Can initiate, but not turn or adjust sheets alone.
      4 = Helpless.
      9 = Information Missing

University of Kansas Medical Center
3901 Rainbow Boulevard   Kansas City, KS 66160
Department of Neurology

☐ Meds Off   ☐ Meds On

Patient Name _____

Med. Rec. No. _____

14. Falling (unrelated to freezing).. _____
0 = None
1 = Rare falling.
2 = Occasionally falls, less than once per day.
3 = Falls an average of once daily.
4 = Falls more than once daily.
9 = Information Missing

15. Freezing when walking .... _____
0 = None
1 = Rare freezing when walking; may have start-hesitation.
2 = Occasional freezing when walking.
3 = Frequent freezing. Occasionally falls from freezing.
4 = Frequent falls from freezing.
9 = Information Missing

16. Walking .... _____
0 = Normal
1 = Mild difficulty. May not swing arms or may tend to drag leg.
2 = Moderate difficulty, but requires little or no assistance.
3 = Severe disturbance of walking, requiring assistance.
4 = Cannot walk at all, even with assistance.
9 = Information Missing

17. Tremor .... R _____
0 = Absent
1 = Slight and infrequently present.   L _____
2 = Moderate; bothersome to patient.
3 = Severe; interferes with many activities.
4 = Marked, interferes with most activities.
9 = Information Missing

18. Sensory complaints related to Parkinsonism .... _____
0 = None
1 = Occasionally has numbness, tingling, or mild aching.
2 = Frequently has numbness, tingling, or aching; not distressing.
3 = Frequent painful sensations.
4 = Excruciating pain.
9 = Information Missing

19. Total Activities of Daily Living Score .... _____

Date _____   **UPDRS**   Page 3 of 8

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III.   MOTOR EXAMINATION

20. Speech... ____

    0 = Normal
    1 = Slight loss of expression, diction and/or volume.
    2 = Monotone, slurred but understandable; moderately impaired.
    3 = Marked impairment, difficult to understand.
    4 = Unintelligible.
    9 = Information Missing

21. Facial expression... ____

    0 = Normal
    1 = Minimal hypomimia, could be normal "poker face".
    2 = Slight but definitely abnormal diminution of facial expression.
    3 = Moderate hypomimia; lips parted some of the time.
    4 = Marked of fixed facies with severe or complete loss of facial expression; lips parted ¼ inch or more.
    9 = Information Missing

22. Tremor at rest... JAW ____

    0 = Absent   RU ____
                                                                                                                   LU ____
    1 = Slight and infrequently present.   RL ____
    2 = Moderate in amplitude, but only intermittently present.   LL ____
    3 = Moderate in amplitude and present most of the time.
    4 = Marked in amplitude and present most of the time.
    9 = Information Missing

23. Action of postural tremor of hands... R ____

    0 = Absent
    1 = Slight and infrequent   L ____
    2 = Moderate in amplitude, present with action.
    3 = Moderate in amplitude with posture holding as well as action.
    4 = Marked in amplitude; interferes with feeding.
    9 = Information Missing

24. Rigidity.. NECK ____

Judged on passive movement of major joints with patient relaxed in sitting position. Cogwheeling to be ignored.   RU ____
                                                                                                                   LU ____
    0 = Absent   RL ____
    1 = Slight or detectable only when activated by mirror or other movements.   LL ____
    2 = Mild to moderate.
    3 = Marked, but full range of motion easily achieved.
    4 = Severe, range of motion achieved with difficulty.
    9 = Information Missing

25. Finger taps.. R ____

    0 = Normal (>= 15/5 sec)
    1 = Mild slowing and/or reduction in amplitude (11-14/5 sec)   L ____
    2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement. (7-10/5 sec)
    3 = Severely impaired. Frequent hesitation in initiating movement or arrests in ongoing movement. (3-6/5 sec)
    4 = Can barely raise index finger. (0-2/5 sec)
    9 = Information missing

26. Hand movements.. R ____

Patient opens and closes hands in rapid succession with widest amplitude possible, each hand separately.

    0 = Normal   L ____
    1 = Mild slowing and/or reduction in amplitude.
    2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
    3 = Severely impaired. Frequent hesitation in initiating movement or arrests in ongoing movement.
    4 = Can barely perform the task.
    9 = Information missing

Date _____   **UPDRS**   Page 4 of 8

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3901 Rainbow Boulevard   Kansas City, KS 66160
Department of Neurology

☐ Meds Off   ☐ Meds On

Patient Name _____

Med. Rec. No. _____

27. Rapid alternating movements of hands..R _____
Pronation/supination movements of hands, vertically or horizontally, with as large an amplitude as possible, both hands simultaneously
                                                                                                                                                                  L _____
      0 = Normal
      1 = Mild slowing and/or reduction in amplitude.
      2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
      3 = Severely impaired. Frequent hesitation in initiating movement or arrests in ongoing movement.
      4 = Can barely perform the task.
      9 = Information Missing

28. Leg agility with knee bent..R _____
Patient taps heel on ground in rapid succession, picking up entire foot. Amplitude should be about 3 inches.
                                                                                                                                                                  L _____
      0 = Normal
      1 = Mild slowing and/or reduction in amplitude.
      2 = Moderately impaired. Definite and early fatiguing.
      3 = Severely impaired. Frequent hesitation in initiating movement or arrests in ongoing movement.
      4 = Can barely perform the task.
      9 = Information Missing

29. Arising from chair..._____
      0 = Normal
      1 = Slow; or may need more than one attempt.
      2 = Pushes self up from arms of seat.
      3 = Tends to fall back and may have to try more than one time, but can get up without help.
      4 = Unable to arise without help.
      9 = Information Missing

30. Posture.._____
      0 = Normal erect
      1 = Not quite erect, slightly stooped posture; could be normal for older person.
      2 = Moderately stooped posture, definitely abnormal; can be slightly to one side.
      3 = Severely stooped posture with kyphosis; can be moderately leaning to one side.
      4 = Marked flexion with extreme abnormality of posture.
      9 = Information Missing

32. Gait..._____
      0 = Normal
      1 = Walks slowly, may shuffle with short steps but no festination or propulsion.
      2 = Walks with difficulty, but requires little or no assistance; may have some festination short steps, or propulsion.
      3 = Severe disturbance of gait, requiring assistance.
      4 = Cannot walk at all, even with assistance.
      9 = Information Missing

33. Postural stability..._____
Response to sudden posterior displacement produced by pull on shoulders while patient erect with eyes open and feet slightly apart. Patient is prepared.
      0 = Normal
      1 = Retropulsion, but recovers unaided.
      2 = Absence of postural response; would fall if not caught by examiner.
      3 = Very unstable, tends to lose balance spontaneously.
      4 = Unable to stand without assistance.
      9 = Information Missing

Date _____   **UPDRS**   Page 5 of 8

34. Body bradykinesia and hypokinesia.. _____
Combining slowness, hesitancy, decreased arm swing, small amplitude, and poverty of movement in general.
    0 = None
     1 = Minimal slowness, giving movement a deliberate character; could be normal for some persons.
     2 = Mild degree of slowness and poverty of movement which is definitely abnormal. Alternatively, some reduced amplitude.
     3 = Moderate slowness, poverty or small amplitude of movement.
     4 = Marked slowness, poverty or small amplitude of movement.
     9 = Information Missing

35. Total Motor Exam Score .... _____

TOTAL Unified Parkinson's Disease Rating Scale (UPDRS) Score .... _____

IV.   **COMPLICATIONS OF THERAPY**

A. Dyskinesias

36. Duration .... _____
What proportion of the waking day are dyskinesias present?
    0 = None
    1 = 1% - 25% of day.
    2 = 26% - 50% of day.
    3 = 51% - 75% of day.
    4 = 76% - 100% of day.
    9 = Information Missing

37. Disability .... _____
How disabling are the dyskinesias?
    0 = Not disabling.
    1 = Mildly disabling.
    2 = Moderately disabling.
    3 = Severely disabling.
    4 = Completely disabling.
    9 = Information Missing

38. Painful dyskinesias .... _____
How painful are the dyskinesias?
    0 = No painful dyskinesias
    1 = Slight
    2 = Moderate
    3 = Severe
    4 = Marked
    9 = Information Missing

39. Presence of early morning dystonia .... _____
    0 = No
    1 = Yes
    9 = Information Missing

B. Clinical fluctuations

40. Are any "off" periods predictable as to timing after a dose of medications? .... _____
    0 = No
    1 = Yes
    9 = Information Missing

41. Are any "off" periods unpredictable as to timing after a dose of medication? .... _____
    0 = No
    1 = Yes
    9 = Information Missing

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Department of Neurology

☐ Meds Off   ☐ Meds On

Patient Name _____

Med. Rec. No. _____

42. Do any of the "off" periods come on suddenly, e.g. over a few seconds?.. _____
    0 = No
    1 = Yes
    9 = Information Missing

43. What proportion of the waking day is the patient "off" on the average?.. _____
    0 = None
    1 = 1% - 25% of day.
    2 = 26% - 50% of day.
    3 = 51% - 75% of day.
    4 = 76% - 100% of day.
    9 = Information Missing

C. Other complications

44. Does the patient have anorexia, nausea, or vomiting?.. _____
    0 = No
    1 = Yes
    9 = Information Missing

45. Does the patient have any sleep disturbances, e.g. insomnia or hypersomnolence?.............................. _____
    0 = No
    1 = Yes
    9 = Information Missing

46. Does the patient have symptomatic orthostasis?.. _____
    0 = No
    1 = Yes
    9 = Information Missing

V.   **Hoehn and Yahr Staging**... H&Y _____

VI.   **Schwab and England staging**... Rater _____

Date _____   **UPDRS**   Page 7 of 8

Impressions

_____

_____

_____

_____

_____

Plan

_____

_____

_____

_____

_____

Return to clinic _____

_____

_____

Signature _____

BDI

Name: _____ Date_____

This questionnaire consists of 21 groups of statements. After reading each group of statements carefully, circle the number (0, 1, 2, or 3) next to the one statement in each group which best describes the way you have been feeling the past week, including today. If several statements within a group seem to apply equally well, circle each one. Be sure to read all the statements in each group before making your choice.

1 0 I do not feel sad.
   1 I feel sad.
   2 I am sad all the time and I can't snap out of it.
   3 I am so sad or unhappy that I can't stand it.

2 0 I am not particularly discouraged about the future.
   1 I feel discouraged about the future.
   2 I feel I have nothing to look forward to.
   3 I feel that the future is hopeless and that things cannot improve.

3 0 I do not feel like a failure.
   1 I feel I have failed more than the average person.
   2 As I look back on my life, all I can see is a lot of failures.
   3 I feel I am a complete failure as a person.

4 0 I get as much satisfaction out of things as I used to.
   1 I don't enjoy things the way I used to.
   2 I don't get real satisfaction out of anything anymore.
   3 I am dissatisfied or bored with everything.

5 0 I don't feel particularly guilty.
   1 I feel guilty a good part of the time.
   2 I feel quite guilty most of the time.
   3 I feel guilty all of the time.
6
   0 I don't feel I am being punished.
   1 I feel I may be punished.
   2 I expect to be punished.
   3 I feel I am being punished.

7 0 I don't feel disappointed in myself.
   1 I am disappointed in myself.
   2 I am disgusted with myself.
   3 I hate myself.

8 0 I don't feel I am any worse than anybody else.
   1 I am critical of myself for my weaknesses or mistakes.
   2 I blame myself all of the time for my faults.
   3 I blame myself for everything bad that happens.

9 0 I don't have any thoughts of killing myself.
   1 I have thoughts of killing myself, but I would not carry them out.
   2 I would like to kill myself.
   3 I would kill myself if I had the chance.

10 0 I don't cry more than usual.
   1 I cry more now than I used to.
   2 I cry all the time now.
   3 I used to be able to cry, but now I can't cry even though I want to.

11 0 I am no more irritated now than I ever am.
   1 I get annoyed or irritated more easily than I used to.
   2 I feel irritated all the time now.
   3 I don't get irritated at all by the things that used to irritate me.

12
0 I have not lost interest in other people.
1 I am less interested in other people than I used to be.
2 I have lost most of my interest in other people.
3 I have lost all of my interest in other people.

13
0 I make decisions about as well as I ever could.
1 I put off making decisions more than I used to.
2 I have greater difficulty in making decisions than before.
3 I can't make decisions at all anymore.

14
0 I don't feel I look any worse than I used to.
1 I am worried that I am looking old or unattractive.
2 I feel that there are permanent changes in my appearance that make me look unattractive.
3 I believe that I look ugly.

15
0 I can work about as well as before.
1 It takes an extra effort to get started at doing something.
2 I have to push myself very hard to do anything.
3 I can't do any work at all.

16
0 I can sleep as well as usual.
1 I don't sleep as well as I used to.
2 I wake up 1-2 hours earlier than usual and find it hard to get back to sleep.
3 I wake up several hours earlier than I used to and cannot get back to sleep.

17
0 I don't get more tired than usual.
1 I get tired more easily than I used to.
2 I get tired from doing almost anything.
3 I am too tired to do anything.

18
0 My appetite is no worse than usual.
1 My appetite is not as good as it used to be.
2 My appetite is much worse now.
3 I have no appetite at all anymore.

19
0 I haven't lost much weight, if any, lately.
1 I have lost more than 5 pounds.
2 I have lost more than 10 pounds.
3 I have lost more than 15 pounds.

I am purposely trying to lose weight by eating less. Yes_____ No _____

20
0 I am no more worried about my health than usual.
1 I am worried about physical problems such as aches and pains; or upset stomach; or constipation.
2 I am very worried about physical problems and it's hard to think of much else.
3 I am so worried about my physical problems that I cannot think about anything else.

21
0 I have not noticed any recent change in my interest in sex.
1 I am less interested in sex than I used to be.
2 I am much less interested in sex now.
3 I have lost interest in sex completely.

Mini-Mental State Examination (MMSE)[1,2*]

Make the patient comfortable and establish rapport. Ask questions in the order listed. *Total possible score is 30.*

Maximum Score	Score	
		ORIENTATION
5	( )	1. "What is the (year) (season) (date) (day) (month)?"
5	( )	2. "Where are we?" (state) (county) (town or city) (hospital) (floor).
		REGISTRATION
3	( )	Ask the patient if you may test his/her memory. Then say the names of 3 unrelated objects, clearly and slowly, about one second for each (eg, "apple," "table," "penny"). After you have said all 3, ask him/her to repeat them. This first repetition determines the score (0-3), but keep saying them until he/she can repeat all 3, up to 6 trials.
		ATTENTION AND CALCULATION
5	( )	Ask the patient to begin with 100 and count backwards by 7. Stop after 5 subtractions (93, 86, 79, 72, 65). Score the total number of correct answers. If the patient cannot or will not perform the serial 7s task, ask him/her to spell the word "WORLD" backwards. The score is the number of letters in the correct order (eg, DLROW = 5; DLRW = 4; DLORW, DLW = 3; OW = 2; DRLWO = 1).
		RECALL
3	( )	Ask the patient to recall the 3 items repeated above (eg, "apple," "table," "penny").
		LANGUAGE
2	( )	**Naming:** Show the patient a wristwatch and ask him/her what it is. Repeat for pencil.
1	( )	**Repetition:** Ask the patient to repeat the phrase "No ifs, ands, or buts" after you.
3	( )	**3-Stage Command:** Give the patient a piece of blank paper and ask him/her to "take a piece of paper in your right hand, fold it in half, put it on the floor." Score 1 point for each part correctly executed.
1	( )	**Reading:** On a blank piece of paper, print the sentence "CLOSE YOUR EYES" in letters large enough for the patient to see clearly. Ask him/her to read it and do what it says. Score 1 point only if he/she actually closes his/her eyes.
1	( )	**Writing:** Give the patient a blank piece of paper and ask him/her to write a sentence. Do not dictate a sentence; it is to be written spontaneously. It must contain a subject and verb and be sensible. Correct grammar and punctuation are not necessary.
1	( )	**Copying:** Ask the patient to copy the figure of intersecting pentagons exactly as it is. All 10 angles must be present and 2 must intersect to form a 4-sided figure to score 1 point. Tremor and rotation are ignored.
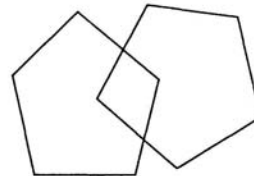
Maximum Total Score	Total Score	Suggested guideline for determining the severity of cognitive impairment:
30	(_____)	Mild: MMSE ≥21
		Moderate: MMSE 10-20
		Severe: MMSE ≤9

Expected decline in MMSE scores in untreated mild to moderate Alzheimer's patient is 2 to 4 points per year.[3,4]

References: 1. Folstein MF, Folstein SE, McHugh PR. "Mini-Mental State": a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res.* 1975;12:189-198. **2.** Cockrell JR, Folstein MF. Mini-Mental State Examination (MMSE). *Psychopharm Bull.* 1988;24:689-692. **3.** Becker JT, Huff FJ, Nebes RD, Holland A, Boller F. Neuropsychological function in Alzheimer's disease: pattern of impairment and rates of progression. *Arch Neurol.* 1988;45:263-268. **4.** Mortimer JA, Ebbit B, Jun S-P, Finch MD. Predictors of cognitive and functional progression in patients with probable Alzheimer's disease. *Neurology.* 1992;42:1689-1696.

<center>**PD Pilot Protocol**</center>

<u>Subject Setup</u>
Participants will be set up at the start of the session. This setup will remain the same for all protocols.

Consent
Clarify history (falls in previous 3 months, severity and duration, medication status)
Mini-mental exam
Change into standard shorts, shoes, and socks.

Measurements and EMG Placement
Have subject lie down in setup room; take the following measurements while subject is lying down:
Leg Length (distance from ASIS to medial ankle via knee)
Inter-ASIS Distance
Place EMGs: bilateral TA, solius, hamstring, quad
     Tips for placement:
     Solius:
     Hamstring: have subject lay on side, then hold their lower leg and ask them to try to
     bend their leg while you resist.
Have subject stand for the following measurements:
Knee Width (between femoral condyles)
Ankle Width (align measuring device with axis of ankle)
Ankle Height
Foot Width
Foot Length
Calf Circumference
Thigh Circumference
Height
Weight

EMG:
Bilateral application of electrodes to the following muscles:
Gastroc, solius, quadriceps, anterior tib, hamstring.

Connect EMG as follows:

EMG lead	Muscle	EMG out-> Vicon BNC in
#1	R TA	9 – 1
#2	R gatroc	10 – 2
#3	R solius/ham	11 – 3
#4	R quad	12 – 4
#5	L TA	13 – 5
#6	L gatroc	14 – 6
#7	L solius/ham	15 – 7
#8	L quad	16 – 8
Black	ground	17 – 9

Vicon markers

15 14 mm markers will be placed on the lower body as follows (see Vicon PlugIn Gait marker placement guide for more information about specific placement methods):

Complete Setup: Bilateral – ASIS, sacrum, thigh, knee, shin, ankle, heel, toe

Knee alignment devices (KADS) will be used during the patient setup to establish the knee joint coordinate system.

Modified Setup: Bilateral- greater trochanter, thigh, knee, shin, ankle, heel, toe

Marker Placement Tips:

ASIS/Sacrum: tape around the waist, and then attach markers to the tape

Thigh: Find greater trochanter, have subject rotate their foot to make sure you have it, then place marker on the line between the greater troch and knee. Place the marker on the right side higher than the left side.

Knee: Identify tibial plateau, then move back and up to find the femoral condyle-Place KADS first, then replace with individual markers.

Shin: Place on line between axis of knee and axis of ankle, marker on the right side higher than left

Heel: Place on shoe, at same height of toe marker

Ankle: Place marker in line of joint

Toe: 2nd metatarsal head

- Put harness on
- Put EMG belt on

Data Collection

Walk the subject over to the forceplates for the EMG check and subject calibration trials.

- **Subject Calibration Trial**
- Remove KADs and replace with knee markers
- EMG check trial

Sway (trial type: PD_sway/ trial name: sway1)

Sway testing consists of three trials in each of two different conditions, eyes open (EO) and eyes closed (EC). Force plate, EMG, and motion data will be collected. Each test will last 30 seconds with 30 seconds of rest in between trials.

Should have complete marker setup, EMG on gastroc, SOLEUS, TA, quads

- Have participant stand comfortably with one foot on each force plate. Feet should be shoulder wide and at a self-selected angle. Arms rest to the side and the subject is looking at a marker placed 5 feet in front of the at approximately eye height.
- Attach safety harness
- Check EMG and visibility of markers
- Read script to the participant
- Before each test, remind the participant of the condition being tested (EO or EC).
- **Disconnect Solius EMG channel and connect to hamstring electrode**

Balance Recovery (trial type: general w/analog/ trial name: pull1)
The balance recovery testing consists of 3 backwards pull trials. Force plate, EMG, and motion data will be collected during all trials. The weight-drop device will be used to pull the participant.
Should have modified marker setup (no sacrum or ASIS, but including great troch markers), EMG on gastroc, hamstring, TA, quad

- Attach safety harness
- **TAKE STATIC TRIAL IN MODIFIED MARKER SETUP**
- Put on the rigid belt
- Measure waist height, adjust pull device to 8.7% of waist height
- Attach pull device cable
- Read script, explaining task (no practice trials)
- Research assistant should spot the participant throughout all trials
- Once subject is ready, release the weight-dropping mechanism
- Tell the subject to relax after they have regained their balance for three seconds
- Check trial in Vicon for marker visibility
- Perform a total of 3 trials with 30 seconds rest in between trials
- Disconnect safety harness, cable to pull device, and remove belt

Gait Initiation (trial type: general w/analog/ trial name: gait_ini1)
Participants will perform 5 gait initiation trials, all starting from standing on a forceplate. EMG, force and movement data will be collected.
Should have complete marker setup, foot switches, EMG on gastroc, hamstring, TA, quad

- Attach foot switches and foot switch belt
- Attach foot switches to scope to check and monitor foot switch signal
- Have participant stand in collection area.
- Attach safety harness
- Read the script to the participant.
- Do a few practice trials to get a good starting location ensuring clean FP strikes.
- Participant should start each trial with their feet in a comfortable stance and their arms relaxed at their sides.
- At the end of the trial, remove the light switch cable and replace with a grounding resistor to AUX 4.
- A research assistant should be spotting the participant throughout.

Gait (trial type: PD_gait/ trial name: gait)
Participant will walk on the treadmill for 3 minutes at a self-selected speed. EMG and movement data will be collected.
Should have complete marker setup, foot switches, EMG on gastroc, hamstring, TA, quad

- Move treadmill into the Vicon collection volume under the safety support.
- Have participant put on safety harness.
- Attach foot switches and foot switch belt
- Attach foot switches to scope to check and monitor foot switch signal

- Instruct participant to step onto the treadmill.
- Attach the cable to the safety harness.
- Attach kill switch to subject's clothing.
- Power up the treadmill.
- Read the script to the participant, explaining the tasks.
- Slowly increase the speed of the treadmill until the desired speed is reached. Record the final speed on the data collection sheet.
- Once the participant has reached a comfortable gait begin data collection.
- At the end of data collection, inform participant they are finished and then stop the treadmill (manually decrease the speed to zero).
- Remove safety cable and assist the participant in stepping off the treadmill.

Take another subject calibration trial (should have two subject calibration trials- one for use with br, one for all others)

Take another force plate zero trial

PD Pilot Protocol: Checklist

Start Equipment Setup:
_____Check Vicon camera positions
_____Cables from force plate amplifiers are labeled "Vicon BOB"
_____BNC connectors from EMG are connected to Vicon BOB.
_____Connect video camera
_____Connect pull device – normal (AUX1), shear (AUX2)
_____Balance force plates

Start Subject Setup:
_____Consent
_____Clarify history (falls in previous 3 months, severity and duration, medication status)
_____Mini-mental exam
_____5 Self-Report Tests

Complete Equipment Setup:
_____Complete Vicon session start-up as in Vicon Collection Procedures (do not calibrate more than 30 minutes prior to testing)
_____Check system configuration (MJF Pilot), analog setup and control setup
_____Zero analog channels for the force plates while in correct session
_____Collect a FP zero trial for tracking drift (trial name: FPzero)
_____Calculate appropriate weight for pull and load pull device (see paper)
_____Test Pull Device
_____Place "GO" switch box and target

Complete Subject Setup:
_____Measurements and EMG Placement
_____Vicon markers
_____Put harness on
_____Put EMG belt on
_____Place KADs for subject calibration trial

Data Collection:
_____Check to make sure Vicon is setup for this experiment
_____Collect a subject calibration trial (trial type: subject calibration/ trial name: static)
_____Check that movie camera is working
_____Check to make sure all markers are visible
_____Remove KADs and replace with knee markers
_____Collect EMG trial (trial type: analog only/ trial name: EMGcheck)
_____Check EMG signal (view→new analog data) (shift-t to zoom)

Sway (trial type: PD_sway/ trial name: sway1) *Comment EO/EC in Vicon*
3 EO/3 EC Each test will last 30 seconds with 30 seconds of rest in between trials.
Should have complete marker setup, EMG on gastroc, SOLEUS, TA, quads

_____Disconnect Solius EMG channel and connect to hamstring electrode

Balance Recovery (trial type: general w/analog/ trial name: pull1)
3 Backward Pull Trials
Should have modified marker setup (no sacrum or ASIS, but including great troch markers), EMG on gastroc, hamstring, TA, quad

_____Change markers: move calf and thigh markers out of alignment with knee, ankle, and hip markers. Add a great troch marker if not already in place. Remove ASIS markers.
_____Take a static trial for use with BR (w/troch markers)
_____ Put on the rigid belt
_____Calculate weight drop height (8.7% of waist height) and adjust- measured from brushes
_____Perform a total of 3 trials with 30 seconds rest in between trials
_____Check each trial in Vicon
_____Remove belt

Gait Initiation (trial type: general w/analog/ trial name: gait_ini1)
5 trials, all starting from standing on a force plate.
Should have complete marker setup, foot switches, EMG on gastroc, hamstring, TA, quad

_____Connect foot switch to Vicon BOB- AUX3
_____Connect light switch to Vicon BOB- AUX4
_____Adjust safety harness so that it is moveable
_____Attach foot switches and foot switch belt
_____Attach foot switches to scope to check and monitor foot switch signal
_____Check each trial in Vicon
_____At the end of all trials, remove the light switch cable and replace with a grounding resistor to AUX 4.

Gait (trial type: PD_gait/ trial name: gait)
Participant will walk on the treadmill for 3 minutes at a self-selected speed.
Should have complete marker setup, foot switches, EMG on gastroc, hamstring, TA, quad

_____Attach foot switches and foot switch box, check signal on scope.
_____Take another force plate zero trial
_____Make sure that you have two static trials

Parkinson's Pilot Study Scripts

Postural Sway

"For this set of tests you will stand here with your hands to your sides and have either your eyes focused on the target in front of you or have them closed. We will do several trials with rest in between. I will tell you when to begin each trial and I will tell you when to relax."

EO:
Instructions to subject:
"For this test, you will stand as still as possible. Focus your gaze at the target in front of you"

EC:
Instructions to subject:
"For this test, you will stand as still as possible with your eyes closed. Keep your eyes closed until the end of the trial."

Gait Initiation

5 trials start with feet on forceplates (capture push off and first step.

Instructions to subject:
"For this set of tests you will start standing still and then begin walking when you see the green light. Keep walking until I tell you to stop. You will take approximately 3-4 steps. We will do several trials with rest in between and there will be two different starting positions."

Repeat for each trial:
"For this test, you will stand here as still as possible and when you see the green light you will start walking forward, looking ahead while you walk."

Balance Recovery

Instructions to subject:

"This study will let us look at your response to a balance disturbance. You will be asked to stand here on these force plates and a cable will be attached to your waist. The cable will pull you backwards and you need to regain your balance. We will have you repeat this several times. We will explain each step and give you a rest between trials."

"First we will have you put on this waist belt, which will be attached to the cable that will pull you for each trial. For your safety, you will wear a safety harness. The harness will catch you if you are unable to regain your balance."

"Now, we will have you place your right foot on this plate and your left one on this plate. Stand comfortably with your feet approximately shoulder-width apart. Please stand quietly

with your hands at your sides. Please remain as still as possible before and after you regain your balance, until I tell you to relax. Do you have any questions?

"Okay, now we will start the test. Please remember to stand up straight and remain still before the pull and after you step."

Gait

Instructions to subject:

"For this test you will walk on this treadmill for approximately 3 minutes at a pace that is comfortable for you. First we will determine a pace and then the test will begin. Again, you will wear a safety harness that will catch you in the event that you lose your balance. Also, if at any time you feel uncomfortable, you can push this button and the treadmill will stop abruptly."

"First, we will start the treadmill slowly and choose a speed that feels like a comfortable, normal walking pace to you. Do you have any questions?"

(Choose pace)

"Now, we will start the test. Just continue to walk normally. The test will last approximately 3 minutes."

Parkinson's Test

Date: _____ **Time:** _____ **Subject #:** _____

Engineer: _____
Engineer: _____
PT: _____

PD Duration: _____

Medications:
Name: _____ **Frequency:** _____ **Last Dose:** _____
Name: _____ **Frequency:** _____ **Last Dose:** _____
Name: _____ **Frequency:** _____ **Last Dose:** _____

Fall History:
Falls in previous 3 months:
Date: _____ **Description:** _____
Date: _____ **Description:** _____
Date: _____ **Description:** _____
Date: _____ **Description:** _____

Mini-Mental Score: _____

Measurements:
Leg Length (ASIS to medial ankle via knee): **L:** _____ **R:** _____
Inter ASIS distance: _____
Knee Width (between femoral condyles): **L:** _____ **R:** _____
Ankle Width: **L:** _____ **R:** _____
Ankle Height: **L:** _____ **R:** _____
Foot Width: **L:** _____ **R:** _____
Foot Length: **L:** _____ **R:** _____
Calf Circumference: **L:** _____ **R:** _____
Calf Length: **L:** _____ **R:** _____
Thigh Circumference: **L:** _____ **R:** _____
Thigh Length: **L:** _____ **R:** _____
Height: _____
Weight: _____
Waist Height: _____

Testing Notes:

Subject Calibration Trial
Static 1: _____
Static 2: _____
EMG Check: _____

Sway(PD_sway)
Sway1: _____

Sway2: _____
Sway3: _____
Sway4: _____
Sway5: _____
Sway6: _____

Balance Recovery (general w/analog capture)
Pull1: _____
Pull2: _____
Pull3: _____

Gait Initiation (general w/analog capture)
Gait_ini1: _____
Gait_ini2: _____
Gait_ini3: _____
Gait_ini4: _____
Gait_ini5: _____

Gait (PD_gait)
Gait: _____

Vicon Collection Procedure

MJF pilot study

Camera and Volume setup

- Set camera locations based on Vicon Camera Setup Sheet for study.
- Check that the volume and surrounding area is free of reflective objects.

Check connections with peripheral equipment

- Force plates: Attach the cables labeled "Vicon Raw" to the force plate amplifiers. These terminate at the Vicon BOB. Make sure the cable from the Vicon BOB is connected to the data station. Power on force plates at least 15 minutes before collection.
- EMG: Attach BNC to the Vicon BOB using channels 1-8.
- Pull device input: Connect to the Vicon BOB - normal to AUX1, shear to AUX2.
- Video (If using): Attach fire wire from camera to the fire wire port of PC.   If the camera cord length is too short, you may use the Dazzle, connecting the fire wire from the camera to Dazzle and fire wire from Dazzle to the PC. Make sure the Dazzle and camera are powered on. The Dazzle should be set at "Pass through".

Power up

- Power up and log into computer 1st, then power up Vicon Datastation. If you do not do this in the correct order, the computer will not be able to find the network.

Turn on all equipment, including cameras and strobes at least 15 minutes before start of a session.

Session setup:

- Start Workstation

- Open Eclipse. In the correct database (Browse→ D: Capture\Data\ **Antonis**.enf), double click on the project level (green icon) to activate it. With this level highlighted, select System| System Configuration
  - Select "**MJF_pilot**" system configuration (not a bad idea to check analog setup to confirm the change in the system settings). The session settings are taken from the active config, so if you build the session before making this change, your settings will be incorrect and you will need to start over.
- Click System | Control Setup and ensure that no remote triggers are enabled (no checks).
- Click System | Start Link to establish a connection to the datastation. This should illuminate the camera strobes. Allow the cameras to be on for 10 minutes before calibrating.
- Click System | Live Monitors to look at the capture volume. Check and adjust camera placement to ensure your capture space is covered and viewed by cameras (a quick check of the volume by walking through it with the wand).
  - If you are not receiving data from a camera, unplug the line to the datastation for that camera (1-3 or 4-6) and replug it in. This will reinitialize that group of cameras.
- Check camera angles and camera sensitivity in Workstation
- Go to System | Calibrate cameras. Make sure all cameras are selected and that the proper calibration props are selected (clinical L-frame and 500mm wand).
- Set the calibration L-frame in place to create the desired coordinate system.
- Perform a static calibration followed by dynamic calibration* and check for acceptable calibration values.
  - Make sure the wand stays in the calibration volume during the capture.
- Enter the calibration information in the log.

  Wand visibility – measure of whether both markers are visible to each camera. Higher is better (<50% = failed).

  Static reproducibility – how well the L frame measured matches expected measurements. Lower is better.

> *Residuals - < 0.1% of the distance from the cameras to the*
> *center of the capture volume. Check the log for acceptable*
> *values, typically 1-1.6 for larger volumes.*

- Build the session (add a new patient, and a new session).
- With the session highlighted, go to System | Calibrate Analog Zero Levels and select the force plate channels. Make sure that the force plates are completely setup before this step (powered on, balanced, etc.) and that there is no load on them.
- Go to System | Live Movie to check the view of the video camera if using it.

Begin Capture with Subject

- Once subject is set up with markers, have them stand in the capture volume. Make sure there is nothing besides markers which appear on the subject (reflective jewelry etc).
- To capture a trial:
    - Select the appropriate trial type
    - Check that the appropriate data will be collected by clicking Types.
    - Give the trial a name and any description desired.

*Note 1: make sure that the person performing the calibration is not wearing anything reflective. This can be checked in live monitor by having the person walk around the capture volume. Also, ensure that your subject is not in view of the cameras if he/she has markers on.

Note 2: if a camera is moved at all during testing you must recalibrate!

**Checking and preliminary processing
- You may want to use diagnostic mode to check video quality.
- Analog data can be checked using Graph | Analog. This data will be the analog data as acted on by the scale factors specified for each channel in the analog setup. The raw data can be visualized by Window | New Analog Data or by double clicking the 'A'.
    Control the data presentation by the following keys with or without shift key:
        L - # of traces
        T – timeline
        G – gain

APPENDIX B: INVERSE DYNAMICS MODEL[1]

[1]Modified from Vaughan, C.L., B.L. Davis, and J.C. O'Connor, *Dynamics of Human Gait*. 1992, Champaign, IL: Human Kinetics Publishers.

 Indicates modification to model calculations

 Indicates change to model figures

Detailed Mathematics Used in *GaitLab*

This appendix contains the detailed mathematics that are used to process the anthropometric, kinematic, and force plate data files. These details have been incorporated in the *GaitLab* program. Because we do not provide a listing of the source code for *GaitLab*, and because the material presented in chapter 3 tends to gloss over many details, we have provided all the necessary details for researchers of human gait in this appendix.

Like chapter 3, this appendix covers five different topics: body segment parameters; linear kinematics; centres of gravity; angular kinematics; and dynamics of joints.

Body Segment Parameters

We have chosen to use a method for predicting body segment parameters that is based on simple geometric modeling combined with the anthropometric data of Chandler *et al.* (1975). The thighs and calves are modelled by right rectangular cylinders, whereas the feet are modelled by right rectangular pyramids. The key point to bear in mind is that our modelling process makes use of dimensional consistency. By this we mean that only parameters that have the composite units of kilograms are used to predict segment mass, and that only parameters with the composite units of kg•m^2 are used to predict segmental moments of inertia. We believe, for example, that it makes little sense to use only total body mass to predict segmental moments of inertia. (This was the method used by Chandler *et al.*, 1975.) We will show later in this section how much better our method is in predicting segment moments of inertia.
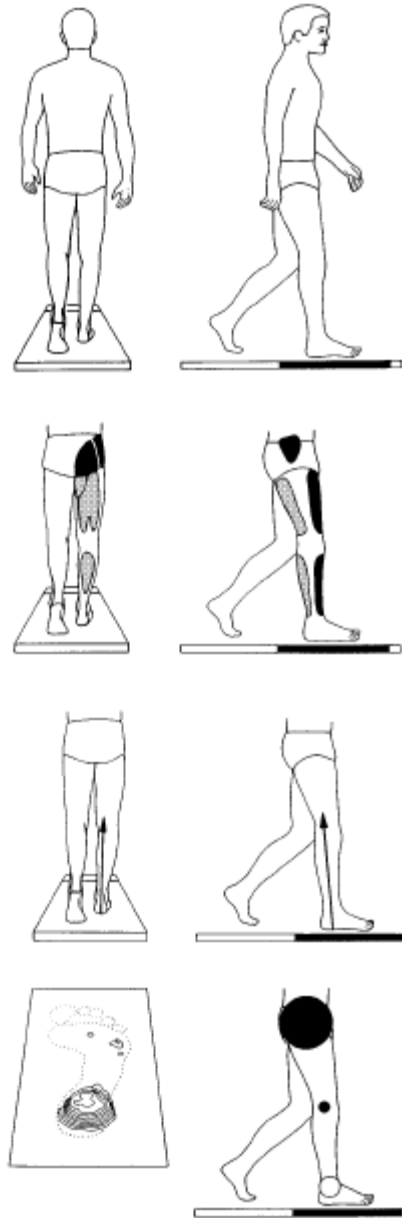
Frame = 4
Time = 0.12 s
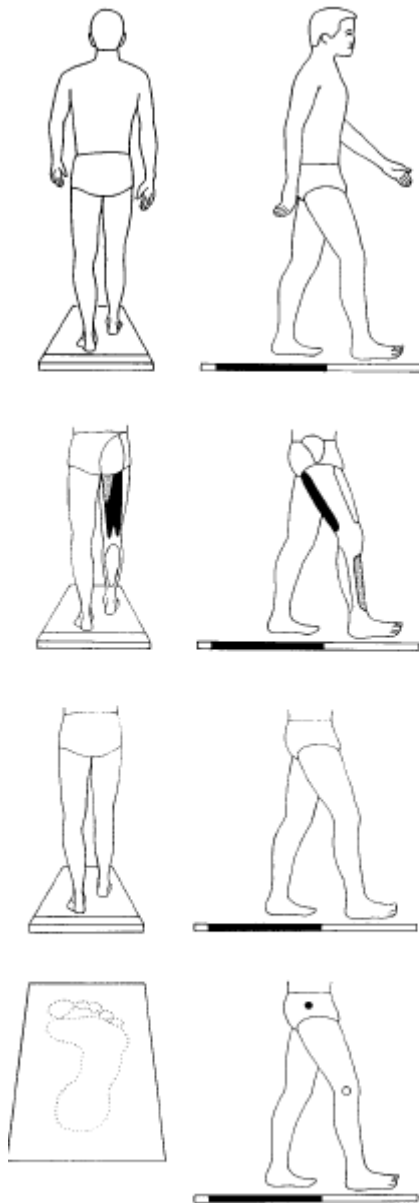
Frame = 28
Time = 1.08 s

Equations 3.1 to 3.3 describe the format and rationale for generating regression equations to predict segment mass based on anthropometric data. The relevant parameters, A_1 through A_{20}, are presented in Table B.1. (A description of how to make these measurements is provided in Table 3.1.) The regression equations that we derived (Equations 3.4 to 3.6 in chapter 3) are based on the six cadavers in Chandler *et al.* (1975) and are repeated here, for sake of completeness, in Table B.2. This table also lists the centre of gravity ratios, which are based on the mean values of the cadavers.

In equations 3.7 to 3.10 and Figure 3.3 we argued for regression equations to predict segmental moments of inertia that are based on body mass in kilograms (kg) times a composite parameter having the dimensions of length squared (m^2). Equation 3.11 was presented as one example (in this case, for the moment of inertia of the thigh about the flexion/extension axis) of such a regression equation. The full set of 18 equations (right and left thighs, calves, and feet, about their flexion/extension, abduction/adduction, internal/external rotation axes) is presented in Table B.3. In trying to understand the relevant axes, refer to Figure 3.3 and 3.10 and the following key:

FlxExt	=	z	axis
AbdAdd	=	y	axis
IntExt	=	x	axis

Table B.1 Anthropometric Data for Calculating Body Segment Parameters and for Predicting Joint Centres and Segment Endpoints

Parameter number	Name
A_1	Total body mass
A_2	Anterior superior iliac spine (ASIS) breadth
A_3	Right thigh length
A_4	Left thigh length
A_5	Right midthigh circumference
A_6	Left midthigh circumference
A_7	Right calf length
A_8	Left calf length
A_9	Right calf circumference
A_{10}	Left calf circumference
A_{11}	Right knee diameter
A_{12}	Left knee diameter
A_{13}	Right foot length
A_{14}	Left foot length
A_{15}	Right malleolus height
A_{16}	Left malleolus height
A_{17}	Right malleolus width
A_{18}	Left malleolus width
A_{19}	Right foot breadth
A_{20}	Left foot breadth

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Table B.2 Equations to Predict the Masses and Centres of Gravity for the Thigh, Calf and Foot

Mass.R.Thigh = (0.1032) * A1 + (12.76) * A3 * A5 * A5 - 1.023;
Mass.L.Thigh = (0.1032) * A1 + (12.76) * A4 * A6 * A6 - 1.023;
Mass.R.Calf = (0.0226) * A1 + (31.33) * A7 * A9 * A9 + 0.016;
Mass.L.Calf = (0.0226) * A1 + (31.33) * A8 * A10 * A10 + 0.016;
Mass.R.Foot = (0.0083) * A1 + (254.5) * A13 * A15 * A17 - 0.065;
Mass.L.Foot = (0.0083) * A1 + (254.5) * A14 * A16 * A18 - 0.065;

CG_Ratio.R.Thigh = 0.39;
CG_Ratio.L.Thigh = 0.39;
CG_Ratio.R.Calf = 0.42;
CG_Ratio.L.Calf = 0.42;
CG_Ratio.R.Foot = 0.44;
CG_Ratio.L.Foot = 0.44;

Note. A1 through A18 are the anthropometric parameters defined in Table B.1. The format of these equations is exactly the same as the C++ code in *GaitLab*.

Table B.3 Equations to Predict Moments of Inertia (I) for the Thigh, Calf, and Foot

I_FlxExt.R.Thigh = 0.00762 * A1 * (A3 * A3 + 0.076 * A5 * A5) + 0.01153;
I_FlxExt.L.Thigh = 0.00762 * A1 * (A4 * A4 + 0.076 * A6 * A6) + 0.01153;
I_AbdAdd.R.Thigh = 0.00726 * A1 * (A3 * A3 + 0.076 * A5 * A5) + 0.01186;
I_AbdAdd.L.Thigh = 0.00726 * A1 * (A4 * A4 + 0.076 * A6 * A6) + 0.01186;
I_IntExt.R.Thigh = 0.00151 * A1 * A5 * A5 + 0.00305;
I_IntExt.L.Thigh = 0.00151 * A1 * A6 * A6 + 0.00305;

I_FlxExt.R.Calf = 0.00347 * A1 * (A7 * A7 + 0.076 * A9 * A9) + 0.00511;
I_FlxExt.L.Calf = 0.00347 * A1 * (A8 * A8 + 0.076 * A10 * A10) + 0.00511;
I_AbdAdd.R.Calf = 0.00387 * A1 * (A7 * A7 + 0.076 * A9 * A9) + 0.00138;
I_AbdAdd.L.Calf = 0.00387 * A1 * (A8 * A8 + 0.076 * A10 * A10) + 0.00138;
I_IntExt.R.Calf = 0.00041 * A1 * A9 * A9 + 0.00012;
I_IntExt.L.Calf = 0.00041 * A1 * A10 * A10 + 0.00012;

I_FlxExt.R.Foot = 0.00023 * A1 * (4 * A15 * A15 + 3 * A13 * A13) + 0.00022;
I_FlxExt.L.Foot = 0.00023 * A1 * (4 * A16 * A16 + 3 * A14 * A14) + 0.00022;
I_AbdAdd.R.Foot = 0.00021 * A1 * (4 * A19 * A19 + 3 * A13 * A13) + 0.00067;
I_AbdAdd.L.Foot = 0.00021 * A1 * (4 * A20 * A20 + 3 * A14 * A14) + 0.00067;
I_IntExt.R.Foot = 0.00141 * A1 * (A15 * A15 + A19 * A19) - 0.00008;
I_IntExt.L.Foot = 0.00141 * A1 * (A16 * A16 + A20 * A20) - 0.00008;

Note. A1 through A20 are the anthropometric parameters defined in Table B.1. The format of these equations is exactly the same as the C++ code in *GaitLab*.

Because we have proposed that a gait analyst should take the time to measure 20 anthropometric parameters (Table B.1) and use these data in our regression equations (Tables B.2 and B.3), it is
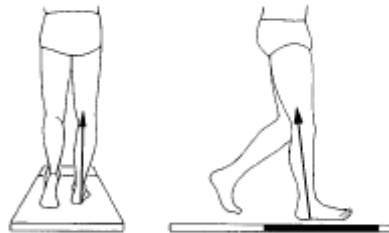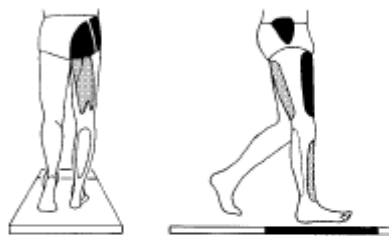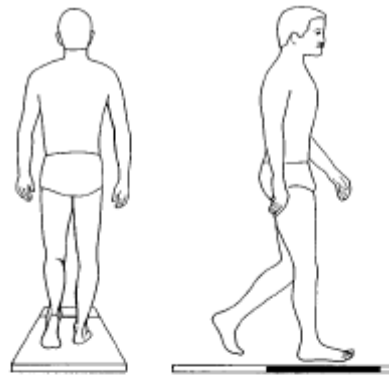
Frame = 5
Time = 0.16 s
Left toe-off
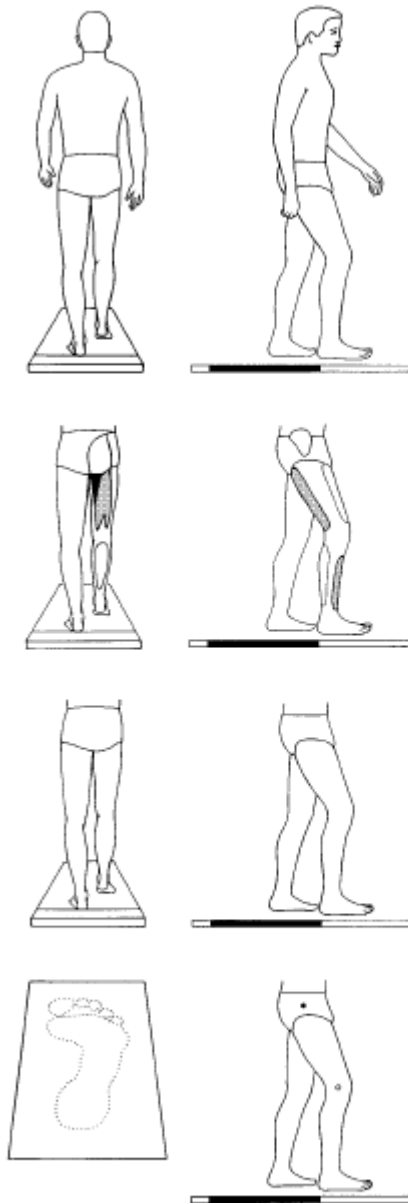
Frame = 24
Time = 0.92 s

reasonable to ask, Is there any benefit? We believe that there *is* a benefit in personalising the BSPs. Chandler *et al.* (1975) derived regression equations based only on total body mass for predicting segmental masses and moments of inertia. Their correlation coefficients, which are a measure of how well their equations fitted the data, are presented in Table B.4. For comparison, our correlation coefficients are also included in this table. Because Equations 3.4 to 3.6 (top of Table B.2) used more than one parameter to predict segment mass (total body mass and a composite parameter representing segment volume), it is necessary to calculate R', the correlation coefficient adjusted to allow for shrinkage:

$$R' = [R^2 - \frac{(p-1)}{N-p} (1 - R^2)]^{\frac{1}{2}} \qquad (B.1)$$

where N is the number of cadavers (6), p is the number of predictors (2), and R is the unadjusted multiple correlation coefficient (Kim & Kohout, 1975). You can see that if p=1 or N>>p, then R' = R.

Note that for each of the segment masses, the adjusted coefficient was substantially better than the simple correlation coefficients of Chandler *et al.* (1975). Note, too, that the correlation coefficients for the moments of inertia equations proposed in the current method were in all cases (except one) markedly higher than those of Chandler. In that one case (the moment of inertia of the thigh

Table B.4 Comparison of Methods Used to Predict Body Segment Parameters for 6 Cadavers of Chandler *et al.* (1975)

Parameter	Segment	Chandler's method	GaitLab method	
		Correlation Coefficient	Correlation Coefficient	Adjusted Coefficient[a]
Mass	Thigh	0.941	0.998	0.997
	Calf	0.917	0.997	0.996
	Foot	0.784	0.899	0.872
Moment of inertia	Thigh			
	FlxExt	0.865	0.901	
	AbdAdd	0.939	0.913	
	IntExt	0.876	0.932	
	Calf			
	FlxExt	0.850	0.972	
	AbdAdd	0.821	0.962	
	IntExt	0.795	0.896	
	Foot			
	FlxExt	0.696	0.899	
	AbdAdd	0.762	0.871	
	IntExt	0.819	0.825	

[a]The correlation coefficients for the *GaitLab* method have to be adjusted for shrinkage because the equations to predict segment mass are based on more than one composite parameter. Refer to text for more detail.

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about the abduction/adduction axis), our coefficient of 0.913 is still quite acceptable. It was not necessary to calculate an adjusted correlation coefficient for our moments of inertia, because only one predictor — a composite parameter having the dimension kilogram •metre •metre (kg•m²) — was used.

We believe that the evidence contained in Table B.4 provides encouraging support for our suggestion that the equations in Tables B.2 and B.3 are of benefit to the gait analyst, who can use these equations to personalise the BSPs of a subject knowing that they work extremely well with the original data from subjects whose sizes and shapes may be quite different from those of the 6 male cadavers of Chandler *et al.* (1975). The equations can be used on children or women or tall basketball players without giving unreasonable answers. The same cannot be said for regression equations, such as those proposed by Hinrichs (1985), that are not dimensionally consistent. This important issue has been addressed by Yeadon and Morlock (1989).

Linear Kinematics

In this section we show how the 15 marker positions (see Figure 3.4 and Table B.5) may be used to accomplish two primary tasks. The first is to calculate uvw reference systems for each segment (see Figures 3.6 to 3.8) to predict the positions of joint centres and segment endpoints (see Equations 3.13 to 3.16). The second task is to use the joint centre positions and the external marker positions (Table B.5) to generate segment reference frames (xyz), which are embedded at the centres of gravity of each segment (see Figure 3.10).

Table B.5 Position Numbers and Names of External Marker Positions

Position number	Name
p_1	Right metatarsal head II
p_2	Right heel
p_3	Right lateral malleolus
p_4	Right tibial wand
p_5	Right femoral epicondyle
p_6	Right femoral wand
p_7	Right anterior superior iliac spine
p_8	Left metatarsal head II
p_9	Left heel
p_{10}	Left lateral malleolus
p_{11}	Left tibial wand
p_{12}	Left femoral epicondyle
p_{13}	Left femoral wand
p_{14}	Left anterior superior iliac spine
p_{15}	Sacrum

From Figure 3.6, we may define the unit vector triad uvw for the right foot as follows:

$$\mathbf{u}_{R.Foot} = (\mathbf{p}_1 - \mathbf{p}_2)/|\mathbf{p}_1 - \mathbf{p}_2| \qquad (B.2)$$
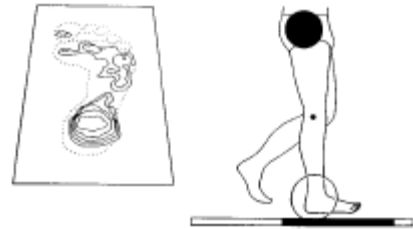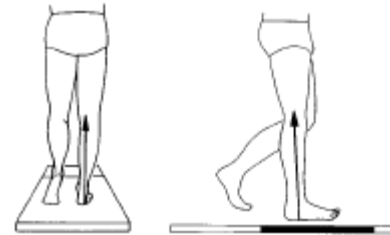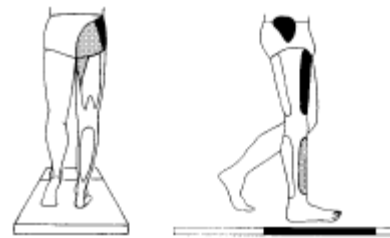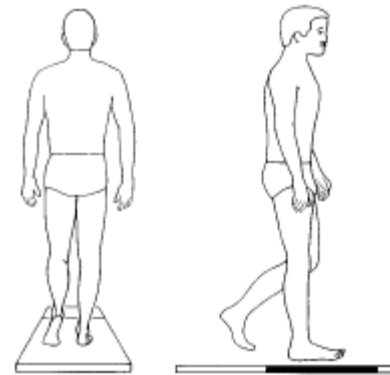
Frame = 6
Time = 0.20 s

Figure 3.7 The three markers (3, 4, and 5), which define the position of the calf in 3-D space. This is an anterior view. The uvw reference system may be used to predict the position of the knee joint.

Figure 3.6 The three markers (1, 2, and 3) which define the position of the foot in 3-D space: (a) side view; (b) view from above. The uvw reference system may be used to predict the position of the ankle and toe.

a   b
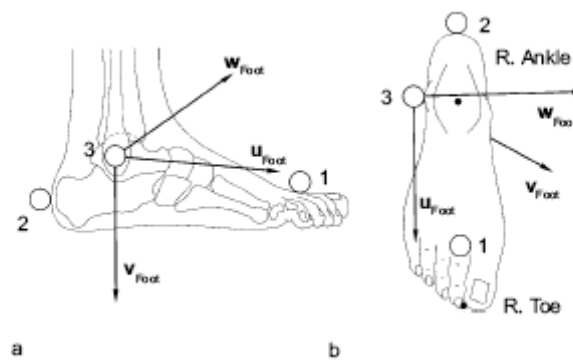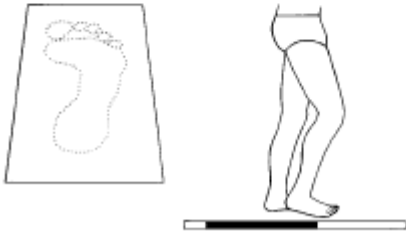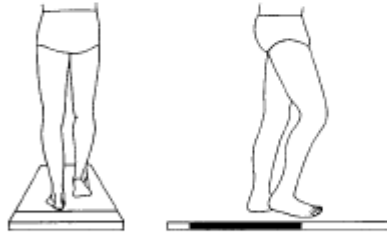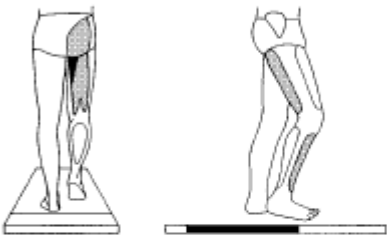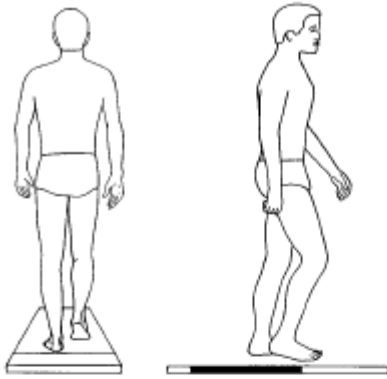
Frame = 23
Time = 0.88 s

$$\mathbf{w}_{\text{R.Foot}} = \frac{(\mathbf{p}_1 - \mathbf{p}_3) \times (\mathbf{p}_2 - \mathbf{p}_3)}{|(\mathbf{p}_1 - \mathbf{p}_3) \times (\mathbf{p}_2 - \mathbf{p}_3)|} \qquad (B.3)$$

$$\mathbf{v}_{\text{R.Foot}} = \mathbf{w}_{\text{R.Foot}} \times \mathbf{u}_{\text{R.Foot}} \qquad (B.4)$$

Then, based on stereo X-rays (Vaughan, 1983), we have the following equations:

$$\mathbf{p}_{\text{R.Ankle}} = \mathbf{p}_3 + 0.016 A_{13}\, \mathbf{u}_{\text{R.Foot}} + 0.392 A_{15} \mathbf{v}_{\text{R.Foot}} \qquad (B.5)$$
$$+ 0.478 A_{17} \mathbf{w}_{\text{R.Foot}}$$

and

$$\mathbf{p}_{\text{R.Toe}} = \mathbf{p}_3 + 0.742 A_{13}\mathbf{u}_{\text{R.Foot}} + 1.074 A_{15}\mathbf{v}_{\text{R.Foot}} \qquad (B.6)$$
$$+ 0.187 A_{19}\mathbf{w}_{\text{R.Foot}}$$

which are the same as Equations 3.13 and 3.14. Similarly, we may calculate the unit vector triad uvw for the left foot as follows:

$$\mathbf{u}_{\text{L.Foot}} = (\mathbf{p}_8 - \mathbf{p}_9)/|\mathbf{p}_8 - \mathbf{p}_9| \qquad (B.7)$$

$$\mathbf{w}_{\text{L.Foot}} = \frac{(\mathbf{p}_8 - \mathbf{p}_{10}) \times (\mathbf{p}_9 - \mathbf{p}_{10})}{|(\mathbf{p}_8 - \mathbf{p}_{10}) \times (\mathbf{p}_9 - \mathbf{p}_{10})|} \qquad (B.8)$$

$$\mathbf{v}_{\text{L.Foot}} = \mathbf{w}_{\text{L.Foot}} \times \mathbf{u}_{\text{L.Foot}} \qquad (B.9)$$

As before, this unit vector triad may be used to estimate the following:

$$\mathbf{p}_{\text{L.Ankle}} = \mathbf{p}_{10} + 0.016 A_{14}\mathbf{u}_{\text{L.Foot}} + 0.392 A_{16}\mathbf{v}_{\text{L.Foot}} \qquad (B.10)$$
$$- 0.478 A_{18}\mathbf{w}_{\text{L.Foot}}$$

and

$$\mathbf{p}_{\text{L.Toe}} = \mathbf{p}_{10} + 0.742 A_{14}\mathbf{u}_{\text{L.Foot}} + 1.074 A_{16}\mathbf{v}_{\text{L.Foot}} \qquad (B.11)$$
$$- 0.187 A_{20}\mathbf{w}_{\text{L.Foot}}$$

which are similar to Equations B.5 and B.6, the main difference being that $\mathbf{w}_{\text{R.Foot}}$ points medially, whereas $\mathbf{w}_{\text{L.Foot}}$ points laterally.

From Figure 3.7, we may define the unit vector triad uvw for the right calf as follows:

$$\mathbf{v}_{\text{R.Calf}} = (\mathbf{p}_3 - \mathbf{p}_5)/|\mathbf{p}_3 - \mathbf{p}_5| \qquad (B.12)$$

$$\mathbf{w}_{\text{R.Calf}} = \frac{(\mathbf{p}_4 - \mathbf{p}_5) \times (\mathbf{p}_3 - \mathbf{p}_5)}{|(\mathbf{p}_4 - \mathbf{p}_5) \times (\mathbf{p}_3 - \mathbf{p}_5)|} \qquad (B.13)$$

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$$\mathbf{u}_{R.Calf} = \mathbf{v}_{R.Calf} \times \mathbf{w}_{R.Calf} \qquad (B.14)$$

We can now calculate the position of the right knee:

$$\mathbf{p}_{R.Knee} = \mathbf{p}_5 + 0.000A_{11}\mathbf{u}_{R.Calf} + 0.000A_{11}\boxed{\text{w r.calf}} \qquad (B.15)$$

$$\boxed{-}\ 0.500A_{11}\boxed{\text{u r.calf}}$$

which is the same as Equation 3.15. Similarly, we may calculate the unit vector triad **uvw** for the left calf as follows:

$$\mathbf{v}_{L.Calf} = (\mathbf{p}_{10} - \mathbf{p}_{12})/|\mathbf{p}_{10} - \mathbf{p}_{12}| \qquad (B.16)$$

$$\mathbf{w}_{Pelvis} = \frac{(\mathbf{p}_{11} - \mathbf{p}_{12}) \times (\mathbf{p}_{10} - \mathbf{p}_{12})}{|(\mathbf{p}_{11} - \mathbf{p}_{12}) \times (\mathbf{p}_{11} - \mathbf{p}_{12})|} \qquad (B.17)$$

$$\mathbf{u}_{L.Calf} = \mathbf{v}_{L.Calf} \times \mathbf{w}_{L.Calf} \qquad (B.18)$$

As before, this vector triad may be used to estimate the position of the left knee:

$$\mathbf{p}_{L.Knee} = \mathbf{p}_{12} + 0.000A_{12}\boxed{\text{w l. calf}} + 0.000A_{12}\mathbf{v}_{L.Calf} \qquad (B.19)$$

$$- 0.500A_{12}\boxed{\text{u l.calf}}$$

which is similar to Equation B.15, the main difference being that $\mathbf{w}_{R.Calf}$ points medially, whereas $\mathbf{w}_{L.Calf}$ points laterally.

From Figure 3.8, we may define the unit vector triad **uvw** for the pelvis as follows:

$$\mathbf{v}_{Pelvis} = (\mathbf{p}_{14} - \mathbf{p}_7)/|\mathbf{p}_{14} - \mathbf{p}_7| \qquad (B.20)$$

$$\mathbf{w}_{L.Calf} = \frac{(\mathbf{p}_7 - \mathbf{p}_{15}) \times (\mathbf{p}_{14} - \mathbf{p}_{15})}{|(\mathbf{p}_7 - \mathbf{p}_{15}) \times (\mathbf{p}_{14} - \mathbf{p}_{15})|} \qquad (B.21)$$

$$\mathbf{u}_{Pelvis} = \mathbf{v}_{Pelvis} \times \mathbf{w}_{Pelvis} \qquad (B.22)$$

This same vector triad may be used to calculate the positions of both the right and left hips:

$$\mathbf{p}_{R.Hip} = \mathbf{p}_{15} + 0.598A_2\mathbf{u}_{Pelvis} - 0.344A_2\mathbf{v}_{Pelvis} \qquad (B.23)$$

$$- 0.290A_2\mathbf{w}_{Pelvis}$$

$$\mathbf{p}_{L.Hip} = \mathbf{p}_{15} + 0.598A_2\mathbf{u}_{Pelvis} + 0.344A_2\mathbf{v}_{Pelvis} \qquad (B.24)$$

$$- 0.290A_2\mathbf{w}_{Pelvis}$$

These equations (B.23 and B.24) for predicting the position of the hip joints are very similar to others in the literature (Campbell *et al.*, 1988; Tylkowski *et al.*, 1982).

Frame = 7
Time = 0.24 s

123
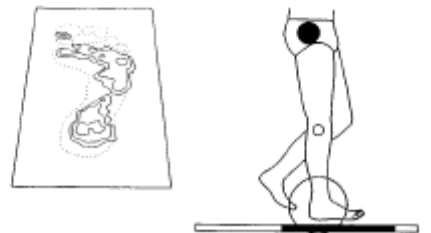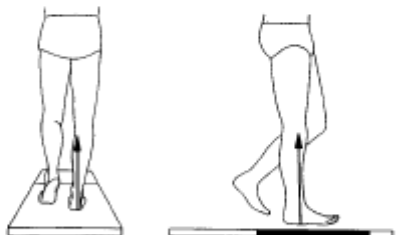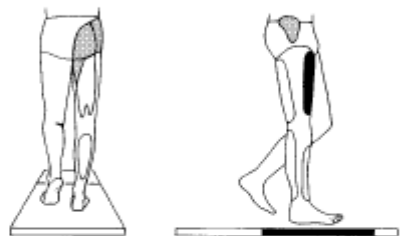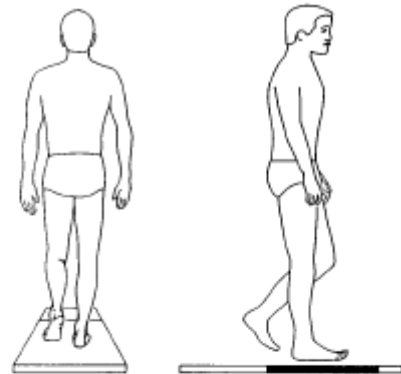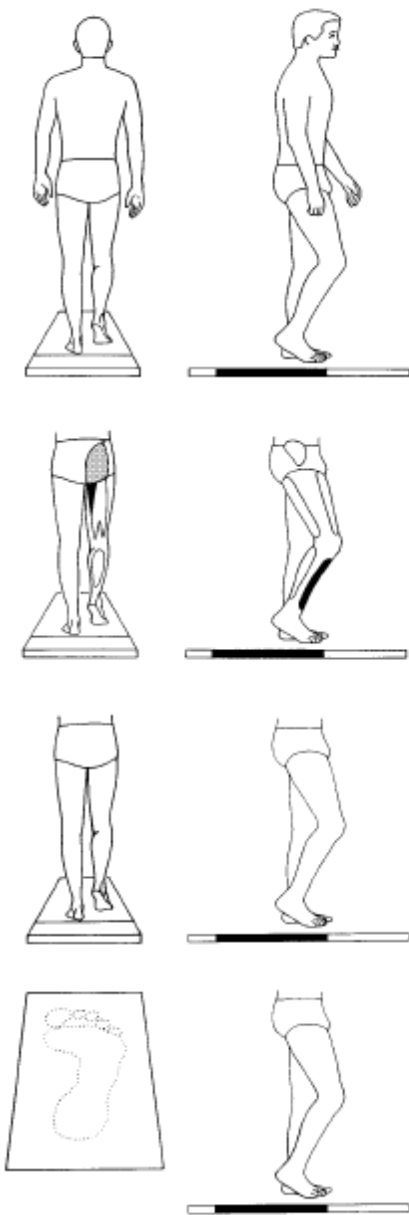
Frame = 22
Time = 0.84 s
Right midswing

The next task is to use the joint centre positions and external marker positions to generate segment reference frames (xyz), which are embedded at the centres of gravity of each segment (see Figure 3.10). There are a few observations that need to be made first:

IJK are the unit vectors in the XYZ directions;
ijk are the unit vectors in the xyz directions.

$$i_{Pelvis} = w_{Pelvis}$$
$$j_{Pelvis} = u_{Pelvis}$$
$$k_{Pelvis} = v_{Pelvis}$$

Segment 1 is the Right Thigh;
Segment 2 is the Left Thigh;
Segment 3 is the Right Calf;
Segment 4 is the Left Calf;
Segment 5 is the Right Foot;
Segment 6 is the Left Foot.

The unit vector triad **ijk** defining the directions of xyz in the segments may be calculated as follows:

Right Thigh

$$i_1 = \frac{(p_{R.Hip} - p_{R.Knee})}{|p_{R.Hip} - p_{R.Knee}|} \tag{B.25}$$

$$j_1 = \frac{(p_6 - p_{R.Hip}) \times (p_{R.Knee} - p_{R.Hip})}{|(p_6 - p_{R.Hip}) \times (p_{R.Knee} - p_{R.Hip})|} \tag{B.26}$$

$$k_1 = i_1 \times j_1 \tag{B.27}$$

Left Thigh

$$i_2 = \frac{(p_{L.Hip} - p_{L.Knee})}{|p_{L.Hip} - p_{L.Knee}|} \tag{B.28}$$

$$j_2 = \frac{(p_{L.Knee} - p_{L.Hip}) \times (p_{13} - p_{L.Hip})}{|(p_{L.Knee} - p_{L.Hip}) \times (p_{13} - p_{L.Hip})|} \tag{B.29}$$

$$k_2 = i_2 \times j_2 \tag{B.30}$$

Right Calf

$$i_3 = \frac{(p_{R.Knee} - p_{R.Ankle})}{|p_{R.Knee} - p_{R.Ankle}|} \tag{B.31}$$

$$j_3 = \frac{(p_5 - p_{R.Knee}) \times (p_{R.Ankle} - p_{R.Knee})}{|(p_5 - p_{R.Knee}) \times (p_{R.Ankle} - p_{R.Knee})|} \tag{B.32}$$

$$k_3 = i_3 \times j_3 \tag{B.33}$$

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Left Calf

$$i_4 = \frac{(p_{L.Knee} - p_{L.Ankle})}{|p_{L.Knee} - p_{L.Ankle}|} \tag{B.34}$$

$$j_4 = \frac{(p_{L.Ankle} - p_{L.Knee}) \times (p_{12} - p_{L.Knee})}{|(p_{L.Ankle} - p_{L.Knee}) \times (p_{12} - p_{L.Knee})|} \tag{B.35}$$

$$k_4 = i_4 \times j_4 \tag{B.36}$$

Right Foot

$$i_5 = \frac{(p_2 - p_{R.Toe})}{|p_2 - p_{R.Toe}|} \tag{B.37}$$

$$k_5 = \frac{(p_{R.Ankle} - p_2) \times (p_{R.Toe} - p_2)}{|(p_{R.Ankle} - p_2) \times (p_{R.Toe} - p_2)|} \tag{B.38}$$

$$j_5 = k_5 \times i_5 \tag{B.39}$$

Left Foot

$$i_6 = \frac{(p_9 - p_{L.Toe})}{|p_9 - p_{L.Toe}|} \tag{B.37}$$

$$k_6 = \frac{(p_{L.Ankle} - p_9) \times (p_{L.Toe} - p_9)}{|(p_{L.Ankle} - p_9) \times (p_{L.Toe} - p_9)|} \tag{B.38}$$

$$j_6 = k_6 \times i_6 \tag{B.42}$$

It is important to realise that although these **ijk** vector triads are used to define the segmental coordinate system xyz, they are actually expressed in terms of the global reference system XYZ. The XYZ coordinates for the **ijk** vector triad of the pelvis and the six lower extremity segments are listed for time = 0.00 s in Table B.6 (which contains the data for the Man.DST file used in *GaitLab*).

Centres of Gravity

This section has three purposes: First, we provide the equations that are used to estimate centres of gravity based on joint centres and segment endpoints; second, we discuss the digital filter that is used to smooth raw position data; and third, we cover the finite difference theory that is the basis for performing numerical differentiation to calculate velocities and accelerations.

From Figure 3.11 and Tables 3.5 and B.2, the following equations may be derived:
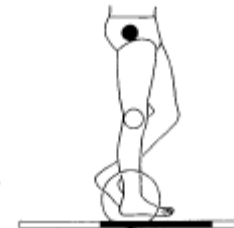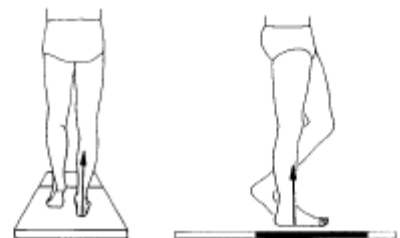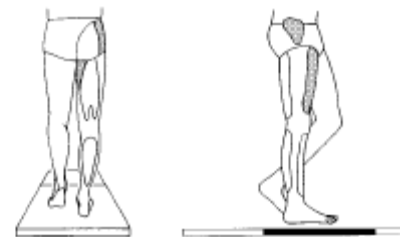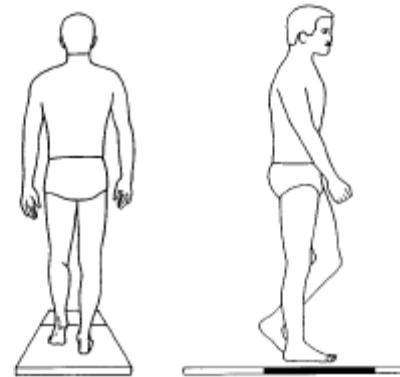
Frame = 8
Time = 0.28 s
Right midstance
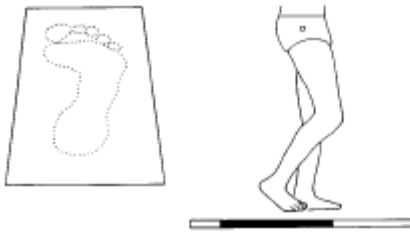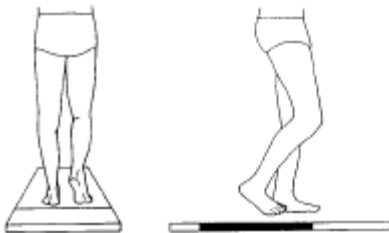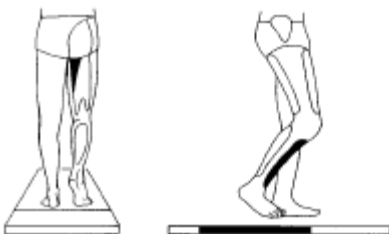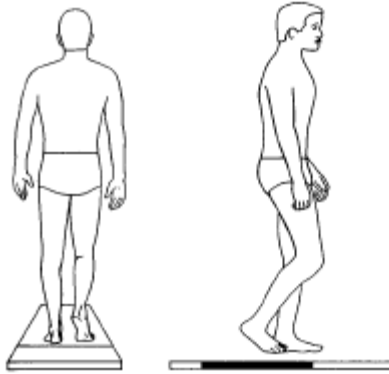
$$p_{R.Thigh.CG} = p_{R.Hip} + 0.39 (p_{R.Knee} - p_{R.Hip}) \qquad (B.43)$$

$$p_{L.Thigh.CG} = p_{L.Hip} + 0.39 (p_{L.Knee} - p_{L.Hip}) \qquad (B.44)$$

$$p_{R.Calf.CG} = p_{R.Knee} + 0.42 (p_{R.Ankle} - p_{R.Knee}) \qquad (B.45)$$

$$p_{L.Calf.CG} = p_{L.Knee} + 0.42 (p_{L.Ankle} - p_{L.Knee}) \qquad (B.46)$$

$$p_{R.Foot.CG} = p_{R.Heel} + 0.44 (p_{R.Toe} - p_{R.Heel}) \qquad (B.47)$$

$$p_{L.Foot.CG} = p_{L.Heel} + 0.44 (p_{L.Toe} - p_{L.Heel}) \qquad (B.48)$$

In human movement activities such as gait, the frequency of the displacement signal is almost always less than the frequency of the noise. The purpose of a digital filter, therefore, is to filter out the high-frequency noise while allowing the low-frequency displacement signal to pass through untouched. The format of a low-pass digital filter is as follows:

$$x'_n = a_0 x_n + a_1 x_{n-1} + a_2 x_{n-2} + b_1 x'_{n-1} + b_2 x'_{n-2} \qquad (B.49)$$

where x' refers to filtered output coordinates, x refers to raw unfiltered coordinate data, n refers to the nth sample frame, and a_0 through b_2 are the filter coefficients. These filter coefficients are constants that depend on the type and order of the filter, the sampling frequency (i.e., the frame rate), and the cutoff frequency (i.e., how much noise should be attenuated). As can be seen from Equation B.49, the filtered output x'_n is a weighted version of the immediate and past raw data, plus a weighted contribution of past filtered output. For the *GaitLab* program, the second-order low-pass Butterworth filter was used. Further details may be obtained in Radar and Gold (1967) and Winter (1979). A FORTRAN listing of the subroutine DIGFIL which implements Equation A.49 may be found in Vaughan (1982).

We pointed out in chapter 3 that the digital filter has endpoint problems, which can lead to erroneous velocities and accelerations in the first few and last few frames. One of the algorithms that does

Table B.6 Three-Dimensional Coordinates of the ijk Unit Vectors for Segment Reference Frames at Time = 0.00 s (Right Heel Strike) for a Normal Male

Segment	i_x	i_y	i_z
Pelvis	-0.072	0.017	0.997
R. Thigh	-0.385	-0.088	0.919
L. Thigh	0.305	-0.001	0.952
R. Calf	-0.213	-0.016	0.977
L. Calf	0.606	0.001	0.795
R. Foot	-0.936	-0.095	-0.339
L. Foot	-0.884	0.043	0.465

Frame = 21
Time = 0.80 s

Segment	j_x	j_y	j_z
Pelvis	0.996	0.053	0.071
R. Thigh	0.922	-0.008	0.386
L. Thigh	0.917	0.272	-0.293
R. Calf	0.977	-0.022	0.212
L. Calf	0.791	0.103	-0.603
R. Foot	-0.298	-0.302	0.906
L. Foot	0.454	0.309	0.835

Segment	k_x	k_y	k_z
Pelvis	-0.052	0.998	-0.021
R. Thigh	-0.026	0.996	0.084
L. Thigh	-0.258	0.962	0.084
R. Calf	0.018	1.000	0.021
L. Calf	-0.083	0.995	0.062
R. Foot	-0.188	0.949	0.254
L. Foot	-0.108	0.950	-0.294

Note. The XYZ values refer to the global coordinate system defined in Figure 3.10.

not have these endpoint problems is the quintic spline (Vaughan, 1982; Wood & Jennings, 1979). We had planned to offer the quintic spline as an option for smoothing and differentiating in the *GaitLab* software, but the size of the code and its running time precluded this option.

We have based our method for determining numerical differentiation on finite difference theory. Finite difference methods may be derived from Taylor series expansions (Miller & Nelson, 1973), and they provide formulae for calculating first and second derivatives of displacement-time data. The first and second derivatives (*i.e.*, velocity and acceleration) are expressible as

$$\frac{dx_n}{dt} = \dot{x}_n = \frac{x_{n+1} - x_{n-1}}{2\Delta t} \quad \text{(B.50)}$$

and

$$\frac{d^2x_n}{dt^2} = \ddot{x}_n = \frac{x_{n+1} - 2x_n + x_{n-1}}{(\Delta t)^2} \quad \text{(B.51)}$$

where x is an input data point, n refers to the nth sample frame, and Δt is the time between adjacent frames. Equations B.50 and B.51 are known as central difference formulae. Forward and backward difference formulae may be used for derivatives of displacement data at the beginning and end of the data set. All these formulae are approximations, because the time interval Δt is not infinitely small. Therefore, any noise in the input signal has a large influence on the accuracy of the derivative values. A FORTRAN listing of the subroutine FIDIFF which implements Equations B.50 and B.51 is also included in the paper by Vaughan (1982).

Frame = 9
Time = 0.32 s

Angular Kinematics

In this section we will cover three areas: definition of anatomical joint angles, definition of segment Euler angles, and derivation of segment angular velocities and accelerations based on the Euler angles.

We stated in chapter 3 that we chose to adopt the methods proposed by Chao (1980) and Grood and Suntay (1983) for defining our anatomical joint angles. Consider the segment reference frames defined in Figure 3.10. The lower extremities have been partitioned into six pairs of segments in Figure B.1, a-f.

The following conventions apply to all six joints:

$k_{Proximal}$ = flexion/extension axis.

i_{Distal} = internal/external rotation axis.

l_{Joint} = abduction/adduction axis.

$$l_{Joint} = \frac{k_{Proximal} \times i_{Distal}}{|k_{Proximal} \times i_{Distal}|} \qquad (B.52)$$

α = flexion/extension angle.

β = abduction/adduction angle.

γ = internal/external rotation angle.

Frame = 20
Time = 0.76 s
Right acceleration

128
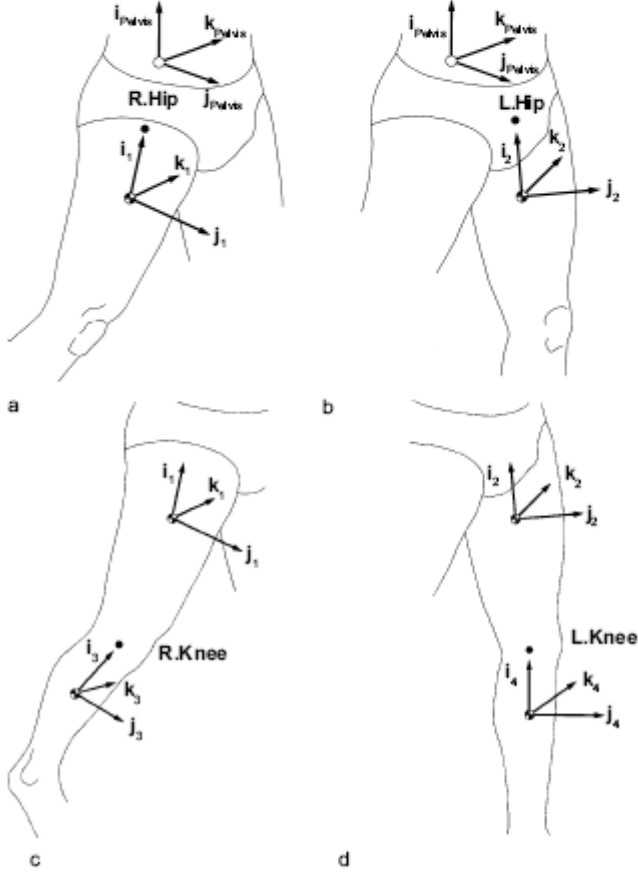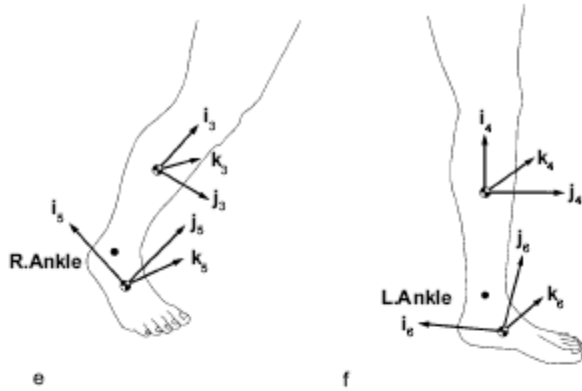
Figure B.1 Unit vector reference frames embedded in the proximal and distal segments on either side of an anatomical joint: (a) right hip; (b) left hip; (c) left knee; (d) left knee; (e) right ankle; (f) left ankle.

Flexion is positive and extension is negative.
Abduction is positive and adduction is negative.
Internal rotation is positive and external rotation is negative.

Using these conventions and the unit vector triads in Figure B.1, we get the following relationships for the anatomical joint angles:

$$\alpha_{R.Hip} = \sin^{-1}[l_{R.Hip} \cdot i_{Pelvis}] \tag{B.53}$$

$$\beta_{R.Hip} = \sin^{-1}[k_{Pelvis} \cdot i_1] \tag{B.54}$$

$$\gamma_{R.Hip} = -\sin^{-1}[l_{R.Hip} \cdot k_1] \tag{B.55}$$

$$\alpha_{L.Hip} = \sin^{-1}[l_{L.Hip} \cdot i_{Pelvis}] \tag{B.56}$$

$$\beta_{L.Hip} = -\sin^{-1}[k_{Pelvis} \cdot i_2] \tag{B.57}$$

$$\gamma_{L.Hip} = \sin^{-1}[l_{L.Hip} \cdot k_2] \tag{B.58}$$

$$\alpha_{R.Knee} = -\sin^{-1}[l_{R.Knee} \cdot i_1] \tag{B.59}$$

$$\beta_{R.Knee} = \sin^{-1}[k_1 \cdot i_3] \tag{B.60}$$

$$\gamma_{R.Knee} = -\sin^{-1}[l_{R.Knee} \cdot k_3] \tag{B.61}$$

$$\alpha_{L.Knee} = -\sin^{-1}[l_{L.Knee} \cdot i_2] \tag{B.62}$$

$$\beta_{L.Knee} = -\sin^{-1}[k_2 \cdot i_4] \tag{B.63}$$

$$\gamma_{L.Knee} = \sin^{-1}[l_{L.Knee} \cdot k_4] \tag{B.64}$$

$$\alpha_{R.Ankle} = \sin^{-1}[l_{R.Ankle} \cdot j_3] \tag{B.65}$$

$$\beta_{R.Ankle} = \sin^{-1}[k_3 \cdot i_5] \tag{B.66}$$

$$\gamma_{R.Ankle} = -\sin^{-1}[l_{R.Ankle} \cdot k_5] \tag{B.67}$$

Frame = 10
Time = 0.36 s

129
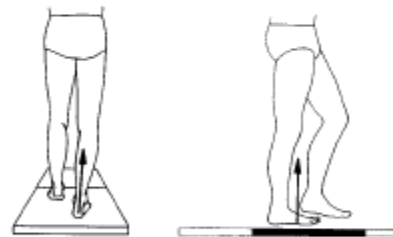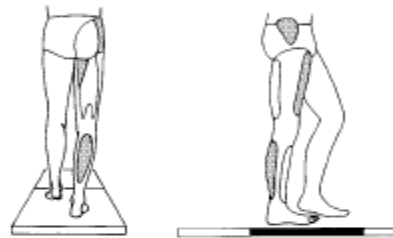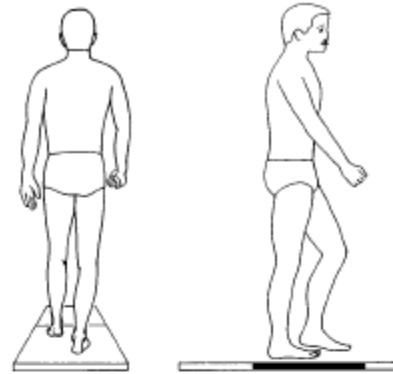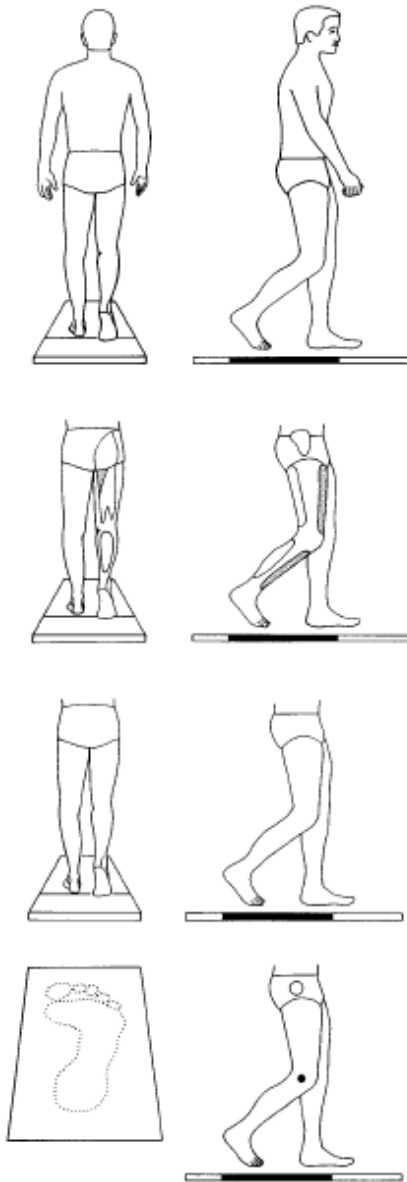
$$\alpha_{L.Ankle} = \sin^{-1}[\mathbf{l}_{L.Ankle} \cdot \mathbf{j}_4] \qquad (B.68)$$

$$\beta_{L.Ankle} = -\sin^{-1}[\mathbf{k}_4 \cdot \mathbf{i}_6] \qquad (B.69)$$

$$\gamma_{L.Ankle} = \sin^{-1}[\mathbf{l}_{L.Ankle} \cdot \mathbf{k}_6] \qquad (B.70)$$

Note that for the angles at the left and right ankle joints, the following conventions apply:

α = plantar flexion (positive) and dorsiflexion (negative)
β = varus (positive) and valgus (negative)
γ = inversion (positive) and eversion (negative)

The neutral position for determining plantar flexion and dorsiflexion is a right angle between the long axes of the calf and foot.

We showed in chapter 3 that a segment reference frame xyz may be oriented in 3-D space relative to the global reference system XYZ by means of three Euler angles. The Euler angle rotations are performed in the following order:

(a) ϕ about the **K** axis of the global reference frame,
(b) θ about the line of nodes, and
(c) ψ about the **k** axis of the segment,

where the line of nodes is a unit vector defined as

$$\mathbf{L} = \frac{(\mathbf{K} \times \mathbf{k})}{|\mathbf{K} \times \mathbf{k}|} \qquad (B.71)$$

By way of example, Figure 3.16 has been expanded into Figure B.2, a-c, which shows each of the Euler angles for a single segment. The angles may be calculated as follows:

$$\phi = \sin^{-1}[(\mathbf{I} \times \mathbf{L}) \cdot \mathbf{K}] \qquad (B.72)$$

$$\theta = \sin^{-1}[(\mathbf{K} \times \mathbf{k}) \cdot \mathbf{L}] \qquad (B.73)$$

$$\psi = \sin^{-1}[(\mathbf{L} \times \mathbf{i}) \cdot \mathbf{k}] \qquad (B.74)$$

Our convention for the definition of the Euler angles is based on two classical mechanics texts by Synge and Griffith (1959) and Goldstein (1965). The segment angular velocities may be obtained from the Euler angles as follows:

$$\dot{\omega}_{segment.x} = \dot{\phi}\sin\theta\sin\psi + \dot{\theta}\cos\psi \qquad (B.75)$$

$$\dot{\omega}_{segment.y} = \dot{\phi}\sin\theta\cos\psi - \dot{\theta}\sin\psi \qquad (B.76)$$

$$\dot{\omega}_{segment.z} = \dot{\phi}\cos\theta + \dot{\psi} \qquad (B.77)$$

where the segment angular velocities ω are given relative to the segment-based reference frame xyz, and the dot above the Euler angles (e.g., $\dot{\phi}$) indicates the first derivative with respect to time (e.g., $\frac{d\phi}{dt}$).

Frame = 19
Time = 0.72 s

By taking the first derivative of Equations B.75 to B.77, we get the segment angular accelerations:

$$\dot{\omega}_{segment\,x} = \ddot{\phi}\sin\theta\sin\psi + \dot{\phi}\dot{\theta}\cos\theta\sin\psi + \qquad (B.78)$$
$$+ \dot{\phi}\dot{\psi}\sin\theta\cos\psi + \ddot{\theta}\cos\psi - \dot{\theta}\dot{\psi}\sin\psi$$

$$\dot{\omega}_{segment\,y} = \ddot{\phi}\sin\theta\cos\psi + \dot{\phi}\dot{\theta}\cos\theta\cos\psi + \qquad (B.79)$$
$$+ \dot{\phi}\dot{\psi}\sin\theta\sin\psi - \ddot{\theta}\sin\psi - \dot{\theta}\dot{\psi}\cos\psi$$

$$\dot{\omega}_{segment\,z} = \ddot{\phi}\cos\theta - \dot{\phi}\dot{\theta}\sin\theta + \ddot{\psi} \qquad (B.80)$$

The Euler angles $\phi\theta\psi$ are smoothed using the digital filter described earlier in this chapter (Equation B.49), whereas finite difference methods (Equations B.50 and B.51) may be used to calculate first and second derivatives.

Dynamics of Joints

We are now at the stage where we can integrate all the previous sections and, using Newton's second and third laws of motion, generate the resultant forces and moments acting at the lower extremity joints. In fact, we will integrate the following:

- Body segment parameters (BSP data)
- Segment centres of gravity, velocities, and accelerations (COG data)
- Ground reactions from force plates (FPL data)
- Joint centres and segment endpoints (JNT data)
- Segment reference frames (REF data)
- Segment angular velocities and accelerations (ANG data)

In performing this integration, we will follow a standard procedure of six steps for each of the segments:

1. Calculate the forces at the proximal joint using the linear form of Newton's second law.
2. Calculate the moment arms, proximal and distal, between the force application point and the segment centre of gravity.
3. Calculate the residual moment acting on the segment.
4. Calculate the rate of change of angular momentum for the segment
5. Calculate the resultant joint moment, first in the xyz system using the angular form of Newton's second law, then in the XYZ system.
6. Convert the joint force and moment from the XYZ system to a body-based system.

It is also pertinent to point out that these six steps are performed first on the foot, then on the calf, and finally on the thigh.

Frame = 11
Time = 0.40 s

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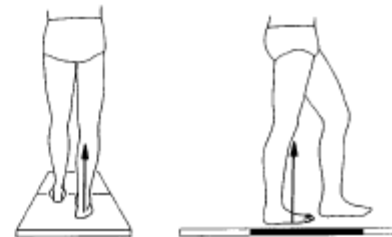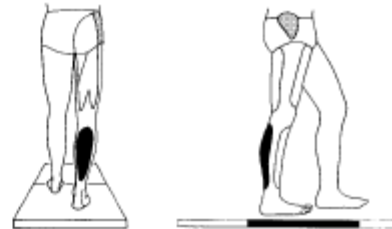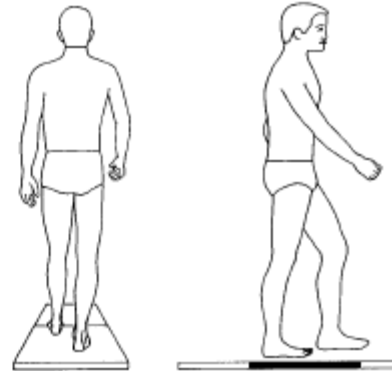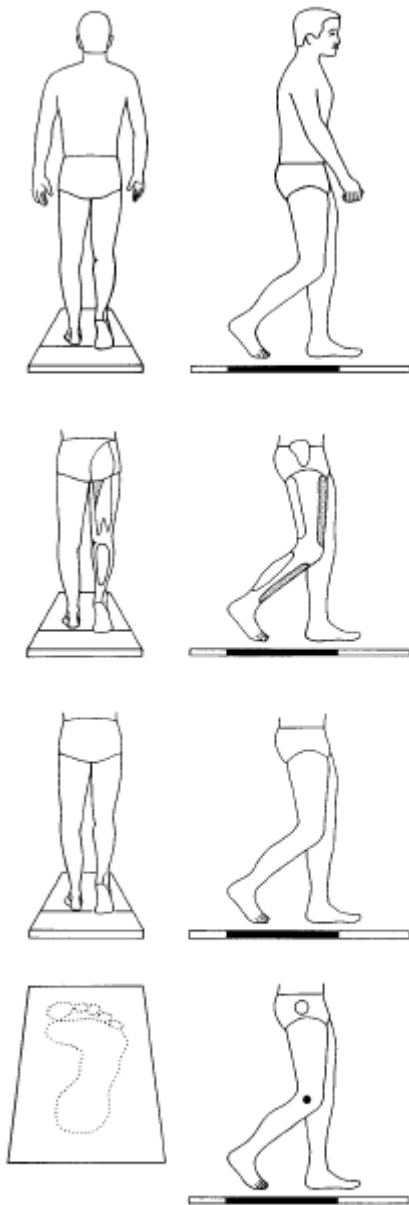
Frame = 18
Time = 0.68 s
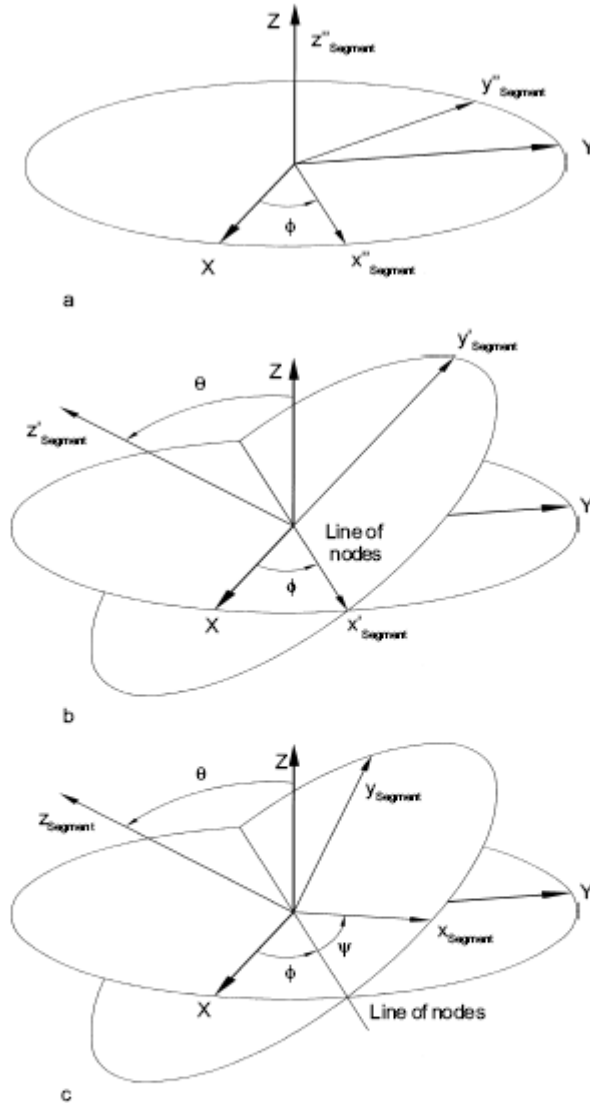
Figure B.2 The three angular degrees of freedom (or Euler angles $\phi_{Segment}$, $\theta_{Segment}$, $\psi_{Segment}$) defining the orientation of a segment's reference axes ($x_{Segment}$, $y_{Segment}$, $z_{Segment}$) relative to the global reference system XYZ (see Goldstein, 1965). Note that the CG has been moved to coincide with the origin of XYZ. The three Euler angle rotations take place in the following order: (a) $\phi_{Segment}$ about the Z axis; (b) $\theta_{Segment}$ about the line of nodes; and (c) $\psi_{Segment}$ about the $z_{Segment}$ axis. The line of nodes is perpendicular to both the Z and $z_{Segment}$ axes. The primes and double primes indicate the intermediate axis positions.

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Because the format for the time rate of change of angular momentum is similar for all segments, angular momentum $\mathbf{H}$ and its first derivative $\dot{\mathbf{H}}$ can be expressed in 3-D in terms of the segment reference frame:

$$\dot{\mathbf{H}}_{Segment} = \dot{H}_{Segment.x}\,\mathbf{i}_{Segment} +$$
$$\dot{H}_{Segment.y}\,\mathbf{j}_{Segment} + \tag{B.81}$$
$$\dot{H}_{Segment.z}\,\mathbf{k}_{Segment}$$

The xyz components can be expressed in terms of moments of inertia, angular velocities, and angular accelerations (Goldstein, 1965):

$$\dot{H}_{Segment.x} = I_{Segment.IntExt}\,\dot{\omega}_{Segment.x} + \tag{B.82}$$
$$(I_{Segment.FlxExt} - I_{Segment.AbdAdd})\omega_{Segment.z}\,\omega_{Segment.y}$$

$$\dot{H}_{Segment.y} = I_{Segment.AbdAdd}\,\dot{\omega}_{Segment.y} + \tag{B.83}$$
$$(I_{Segment.IntExt} - I_{Segment.FlxExt})\omega_{Segment.x}\,\omega_{Segment.z}$$

$$\dot{H}_{Segment.z} = I_{Segment.FlxExt}\,\dot{\omega}_{Segment.z} + \tag{B.84}$$
$$(I_{Segment.AbdAdd} - I_{Segment.IntExt})\omega_{Segment.y}\,\omega_{Segment.x}$$

Right Foot. Application of the linear form of Newton's second law to the right foot yields the following:

$$F_{R.Ankle.X} = m_{R.Foot}\ddot{X}_{R.FootCG} - F_{Plate1.X} \tag{B.85}$$
$$F_{R.Ankle.Y} = m_{R.Foot}\ddot{Y}_{R.FootCG} - F_{Plate1.Y} \tag{B.86}$$
$$F_{R.Ankle.Z} = m_{R.Foot}(\ddot{Z}_{R.FootCG} + 9.81) - F_{Plate1.Z} \tag{B.87}$$

The proximal (Prx) and distal (Dis) moment arms may be calculated as follows:

$$p_{Prx.5} = p_{R.Ankle} - p_{R.FootCG} \tag{B.88}$$

and

$$p_{Dis.5} = p_{Plate1} - p_{R.FootCG} \tag{B.89}$$

where

$$p_{Plate1} = DX1\mathbf{I} + DY1\mathbf{J} + 0\mathbf{K} \tag{B.90}$$

(The subscript 5 indicates the right foot.) The residual (Res) moment acting on the right foot is

$$M_{Res.5} = T_{Plate1} + (p_{Prx.5} \times F_{R.Ankle}) \tag{B.91}$$
$$+ (p_{Dis.5} \times F_{Plate1})$$

and

$$T_{Plate1} = 0\mathbf{I} + 0\mathbf{J} + T_{Z.Plate1}\,\mathbf{K} \tag{B.92}$$

Frame = 12
Time = 0.44 s

133
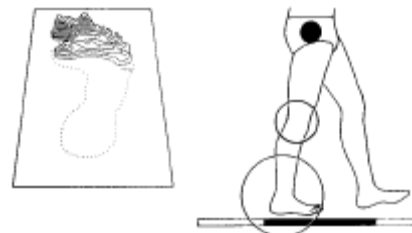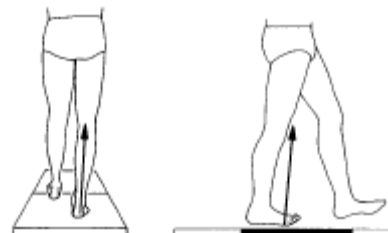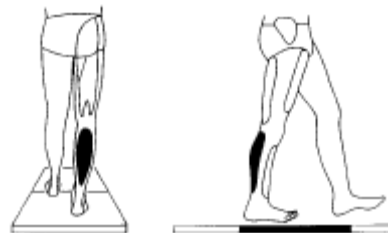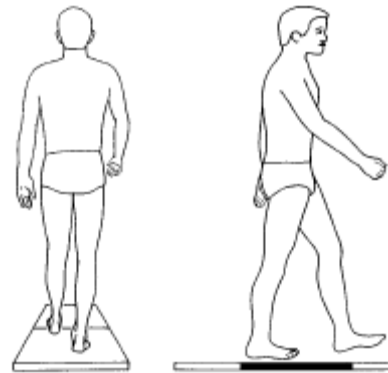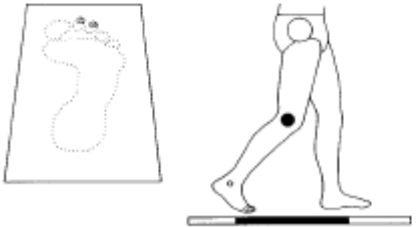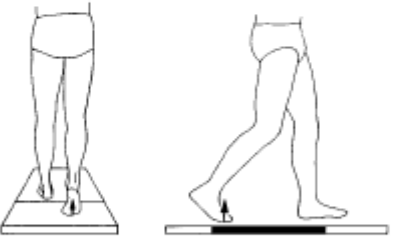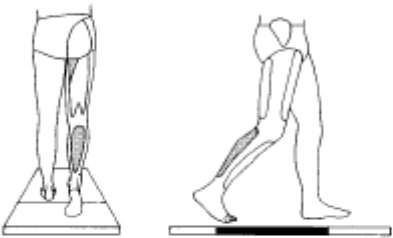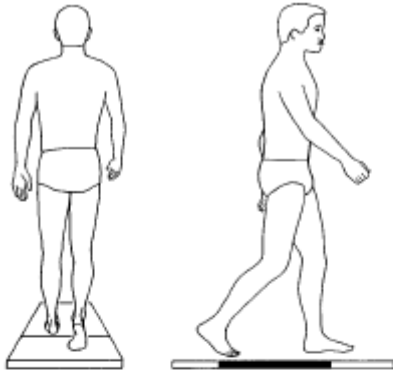
The rate of change of angular momentum for the right foot may be calculated using the standardised form of Equations B.82 to B.84. Then, application of the angular analogue of Newton's second law yields

$$M_{R.Ankle.x} = \dot{H}_{5x} - \mathbf{i}_5 \cdot \mathbf{M}_{Res.5} \qquad (B.93)$$

$$M_{R.Ankle.y} = \dot{H}_{5y} - \mathbf{j}_5 \cdot \mathbf{M}_{Res.5} \qquad (B.94)$$

and

$$M_{R.Ankle.z} = \dot{H}_{5z} - \mathbf{k}_5 \cdot \mathbf{M}_{Res.5} \qquad (B.95)$$

Adding these components gives

$$\mathbf{M}_{R.Ankle} = M_{R.Ankle.x}\,\mathbf{i}_5 + M_{R.Ankle.y}\,\mathbf{j}_5 + M_{R.Ankle.z}\,\mathbf{k}_5 \qquad (B.96)$$

Because $\mathbf{i}_5,\mathbf{j}_5,\mathbf{k}_5$ are expressed in terms of the **IJK** (or XYZ) reference system (see Table B.6), Equation B.96 expresses $\mathbf{M}_{R.Ankle}$ also in terms of the XYZ system. From Equations B.85 to B.87,

$$\mathbf{F}_{R.Ankle} = F_{R.Ankle.X}\mathbf{I} + F_{R.Ankle.Y}\mathbf{J} + F_{R.Ankle.Z}\mathbf{K} \qquad (B.97)$$

Equations B.97 and B.96 provide us with the resultant joint force (**F**) and moment (**M**) of the right calf acting on the right foot. These two vectors are expressed in terms of the global reference system XYZ. However, from an anatomical point of view, it makes far more sense to express the force and moment in terms of a body-based coordinate system. We have chosen to use the same coordinate systems that were used to calculate the anatomical joint angles (see Equations B.53 to B.70). Remember, too, that the resultant force or moment is being exerted by the proximal segment on the distal segment. Therefore, we get the following components:

$$F_{R.Ankle.ProDis} = \mathbf{F}_{R.Ankle} \cdot \mathbf{i}_5 \qquad (B.98)$$

$$F_{R.Ankle.MedLat} = \mathbf{F}_{R.Ankle} \cdot \mathbf{k}_3 \qquad (B.99)$$

$$F_{R.Ankle.AntPos} = \mathbf{F}_{R.Ankle} \cdot \mathbf{l}_{R.Ankle} \qquad (B.100)$$

Also,

$$M_{R.Ankle.InvEve} = \mathbf{M}_{R.Ankle} \cdot \mathbf{i}_5 \qquad (B.101)$$

$$M_{R.Ankle.PlaDor} = \mathbf{M}_{R.Ankle} \cdot \mathbf{k}_3 \qquad (B.102)$$

$$M_{R.Ankle.VarVal} = -\mathbf{M}_{R.Ankle} \cdot \mathbf{l}_{R.Ankle} \qquad (B.103)$$

Right Calf. Application of the linear form of Newton's second law to the right calf yields the following:

$$F_{R.Knee.X} = m_{R.Calf}\ddot{X}_{R.Calf.CG} - F_{R.Ankle.X} \qquad (B.104)$$

$$F_{R.Knee.Y} = m_{R.Calf}\ddot{Y}_{R.Calf.CG} - F_{R.Ankle.Y} \qquad (B.105)$$

$$F_{R.Knee.Z} = m_{R.Calf}(\ddot{Z}_{R.Calf.CG} + 9.81) - F_{R.Ankle.Z} \qquad (B.106)$$

Frame = 17
Time = 0.64 s

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The proximal (Prx) and distal (Dis) moment arms may be calculated as follows:

$$\mathbf{p}_{Prx.3} = \mathbf{p}_{R.Knee} - \mathbf{p}_{R.Calf.CG} \tag{B.107}$$

and

$$\mathbf{p}_{Dis.3} = \mathbf{p}_{R.Ankle} - \mathbf{p}_{R.Calf.CG} \tag{B.108}$$

where the subscript 3 refers to the right calf. The residual (Res) moment acting on the right calf is

$$\mathbf{M}_{Res.3} = - \mathbf{M}_{R.Ankle} - (\mathbf{p}_{Dis.3} \times \mathbf{F}_{R.Ankle}) \tag{B.109}$$
$$+ (\mathbf{p}_{Prx.3} \times \mathbf{F}_{R.Knee})$$

The rate of change of angular momentum for the right calf may be calculated using the standardised form of Equations B.82 to B.84. Then, application of the angular analogue of Newton's second law yields the following:

$$M_{R.Knee.x} = \dot{H}_{3x} - \mathbf{i}_3 \cdot \mathbf{M}_{Res3} \tag{B.110}$$

$$M_{R.Knee.y} = \dot{H}_{3y} - \mathbf{j}_3 \cdot \mathbf{M}_{Res3} \tag{B.111}$$

$$M_{R.Knee.z} = \dot{H}_{3z} - \mathbf{k}_3 \cdot \mathbf{M}_{Res3} \tag{B.112}$$

Adding these components gives

$$\mathbf{M}_{R.Knee} = M_{R.Knee.x}\,\mathbf{i}_3 + M_{R.Knee.y}\,\mathbf{j}_3 + M_{R.Knee.z}\,\mathbf{k}_3 \tag{B.113}$$

Again, we can express the resultant joint force (F; Equations B.104 to B.106) and resultant joint moment (M; Equation B.113) in terms of a body-based coordinate system:

$$F_{R.Knee.PrxDis} = \mathbf{F}_{R.Knee} \cdot \mathbf{i}_3 \tag{B.114}$$

$$F_{R.Knee.MedLat} = \mathbf{F}_{R.Knee} \cdot \mathbf{k}_1 \tag{B.115}$$

$$F_{R.Knee.AntPos} = \mathbf{F}_{R.Knee} \cdot \mathbf{l}_{R.Knee} \tag{B.116}$$

Also,

$$M_{R.Knee.IntExt} = \mathbf{M}_{R.Knee} \cdot \mathbf{i}_3 \tag{B.117}$$

$$M_{R.Knee.FlxExt} = \mathbf{M}_{R.Knee} \cdot \mathbf{k}_1 \tag{B.118}$$

$$M_{R.Knee.AbdAdd} = - \mathbf{M}_{R.Knee} \cdot \mathbf{l}_{R.Knee} \tag{B.119}$$
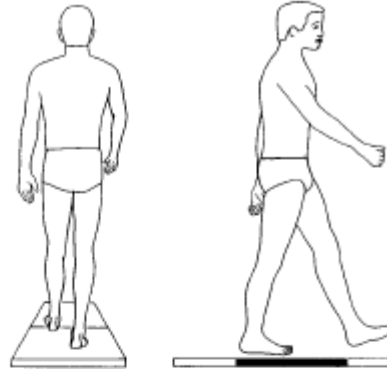
Right Thigh. Application of the linear form of Newton's second law to the right thigh yields the following:

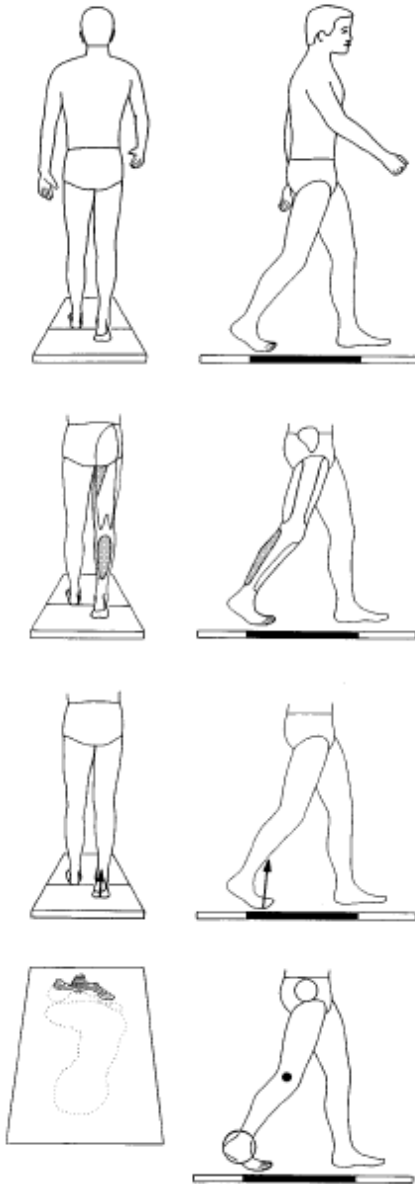$$F_{R.Hip.X} = m_{R.Thigh}\ddot{X}_{R.Thigh.CG} - F_{R.Knee.X} \tag{B.120}$$

$$F_{R.Hip.Y} = m_{R.Thigh}\ddot{Y}_{R.Thigh.CG} - F_{R.Knee.Y} \tag{B.121}$$

$$F_{R.Hip.Z} = m_{R.Thigh}(\ddot{Z}_{R.Thigh.CG} + 9.81) - F_{R.Knee.Z} \tag{B.122}$$

The proximal (Prx) and distal (Dis) moment arms may be calculated
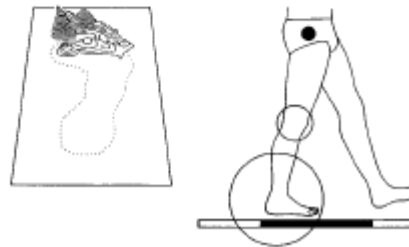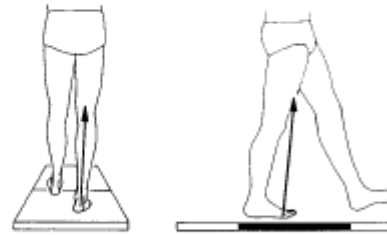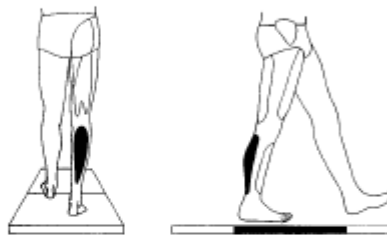
Frame = 13
Time = 0.48 s
Left heel strike

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as follows:

$$p_{Prx.1} = p_{R.Hip} - p_{R.Thigh.CG} \quad \text{(B.123)}$$

and

$$p_{Dis.1} = p_{R.Knee} - p_{R.Thigh.CG} \quad \text{(B.124)}$$

where the subscript 1 refers to the right thigh. The residual (Res) moment acting on the right thigh is

$$M_{Res.1} = - M_{R.Knee} - (p_{Dis.1} \times F_{R.Knee}) \quad \text{(B.125)}$$
$$+ (p_{Prx.1} \times F_{R.Hip})$$

The rate of change of angular momentum for the right thigh may be calculated using the standardised form of Equations B.82 to B.84. Then, application of the angular analogue of Newton's second law yields the following:

$$M_{R.Hip.x} = \dot{H}_{1x} - i_1 \cdot M_{Res1} \quad \text{(B.126)}$$
$$M_{R.Hip.y} = \dot{H}_{1y} - j_1 \cdot M_{Res1} \quad \text{(B.127)}$$
$$M_{R.Hip.z} = \dot{H}_{1z} - k_1 \cdot M_{Res1} \quad \text{(B.128)}$$

Adding these components gives

$$M_{R.Hip} = M_{R.Hip.x} \, i_1 + M_{R.Hip.y} \, j_1 + M_{R.Hip.z} \, k_1 \quad \text{(B.129)}$$
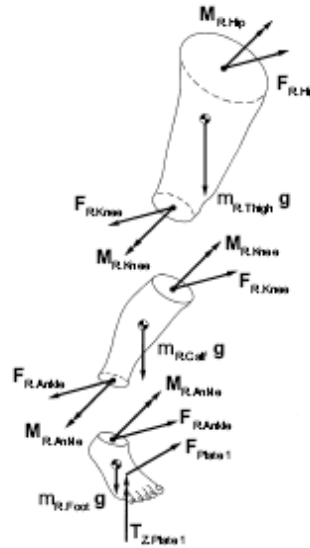
Figure B.3 Free body diagrams for the right foot, calf, and thigh, showing the external forces acting on each segment. Note that the forces and moments at the ankle and knee joints are equal in magnitude but opposite in direction, depending on the segment concerned (Newton's third law).

Frame = 16
Time = 0.60 s

136

We can express the resultant joint force (**F**; Equations B.120 to B.122) and resultant joint moment (**M**; Equation B.129) in terms of a body-based coordinate system:

$$F_{R.Hip.ProxDis} = \mathbf{F}_{R.Hip} \cdot \mathbf{i}_1 \qquad (B.130)$$

$$F_{R.Hip.MedLat} = \mathbf{F}_{R.Hip} \cdot \mathbf{k}_{Pelvis} \qquad (B.131)$$

$$F_{R.Hip.AntPos} = \mathbf{F}_{R.Hip} \cdot \mathbf{l}_{R.Hip} \qquad (B.132)$$

Also,

$$M_{R.Hip.IntExt} = \mathbf{M}_{R.Hip} \cdot \mathbf{i}_1 \qquad (B.133)$$

$$M_{R.Hip.FlxExt} = -\mathbf{M}_{R.Hip} \cdot \mathbf{k}_{Pelvis} \qquad (B.134)$$

$$M_{R.Hip.AbdAdd} = -\mathbf{M}_{R.Hip} \cdot \mathbf{l}_{R.Hip} \qquad (B.135)$$

See the right leg free body diagrams in Figure B.3.

Left Foot. Application of the linear form of Newton's second law to the left foot yields the following:

$$F_{L.Ankle.X} = m_{L.Foot} \ddot{X}_{L.Foot.CG} - F_{Plate2.X} \qquad (B.136)$$

$$F_{L.Ankle.Y} = m_{L.Foot} \ddot{Y}_{L.Foot.CG} - F_{Plate2.Y} \qquad (B.137)$$

$$F_{L.Ankle.Z} = m_{L.Foot}(\ddot{Z}_{L.Foot.CG} + 9.81) - F_{Plate2.Z} \qquad (B.138)$$

The proximal (Prx) and distal (Dis) moment arms may be calculated as follows:

$$p_{Prx.6} = p_{L.Ankle} - p_{L.FootCG} \qquad (B.139)$$

and

$$p_{Dis.6} = p_{Plate2} - p_{L.Foot.CG} \qquad (B.140)$$

where

$$p_{Plate2} = DX2\mathbf{I} + DY2\mathbf{J} + 0\mathbf{K} \qquad (B.141)$$

(The subscript 6 indicates the left foot.) The residual (Res) moment acting on the left foot is

$$\mathbf{M}_{Res.6} = \mathbf{T}_{Plate2} + (p_{Prx.6} \times F_{L.Ankle}) \qquad (B.142)$$
$$+ (p_{Dis.6} \times F_{Plate1})$$

and

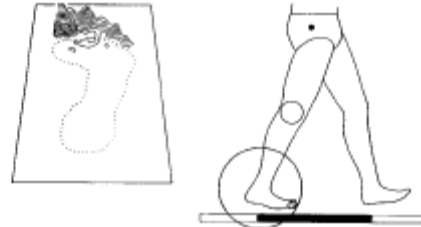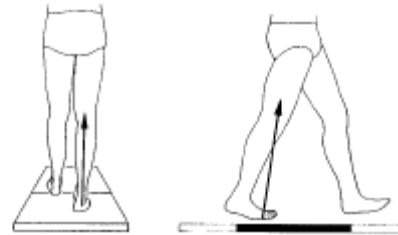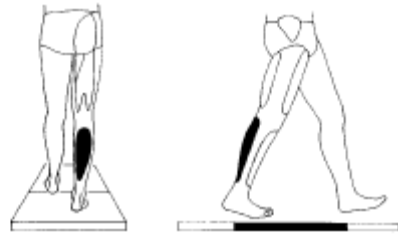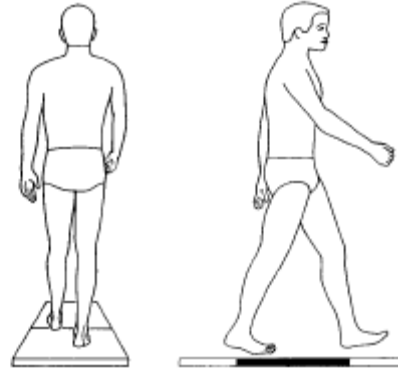$$\mathbf{T}_{Plate2} = 0\mathbf{I} + 0\mathbf{J} + T_{Z.Plate2}\mathbf{K} \qquad (B.143)$$

The rate of change of angular momentum for the left foot may be calculated using the standardised form of Equations B.82 to B.84. Then, application of the angular analogue of Newton's second law yields

$$M_{L.Ankle.x} = \dot{H}_{6x} - \mathbf{i}_6 \cdot \mathbf{M}_{Res.6} \qquad (B.144)$$
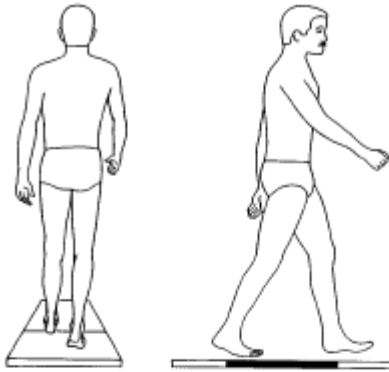
$$M_{L.Ankle.y} = \dot{H}_{6y} - \mathbf{j}_6 \cdot \mathbf{M}_{Res.6} \qquad (B.145)$$

and

$$M_{L.Ankle.z} = \dot{H}_{6z} - \mathbf{k}_6 \cdot \mathbf{M}_{Res.6} \qquad (B.146)$$

Frame = 14
Time = 0.52 s

Frame = 15
Time = 0.56 s
Right heel-off

Adding these components gives

$$\mathbf{M}_{L.Ankle} = M_{L.Ankle.x}\,\mathbf{i}_6 + M_{L.Ankle.y}\,\mathbf{j}_6 \qquad (B.147)$$
$$+ M_{L.Ankle.z}\,\mathbf{k}_6$$

Again, we can express the resultant joint force ($\mathbf{F}$; Equations B.136 to B.138) and resultant joint moment ($\mathbf{M}$; Equation B.147) in terms of a body-based coordinate system:

$$F_{L.Ankle.PrxDis} = \mathbf{F}_{L.Ankle} \cdot \mathbf{i}_6 \qquad (B.148)$$

$$F_{L.Ankle.MedLat} = -\,\mathbf{F}_{L.Ankle} \cdot \mathbf{k}_4 \qquad (B.149)$$

$$F_{L.Ankle.AntPos} = \mathbf{F}_{L.Ankle} \cdot \mathbf{l}_{L.Ankle} \qquad (B.150)$$

Also,

$$M_{L.Ankle.InvEve} = -\,\mathbf{M}_{L.Ankle} \cdot \mathbf{i}_6 \qquad (B.151)$$

$$M_{L.Ankle.PlaDor} = \mathbf{M}_{L.Ankle} \cdot \mathbf{k}_4 \qquad (B.152)$$

$$M_{L.Ankle.VarVal} = \mathbf{M}_{L.Ankle} \cdot \mathbf{l}_{R.Ankle} \qquad (B.153)$$

Left Calf. Application of the linear form of Newton's second law to the left calf yields the following:

$$F_{L.Knee.X} = m_{L.Calf}\ddot{X}_{L.CalfCG} - F_{L.Ankle.X} \qquad (B.154)$$

$$F_{L.Knee.Y} = m_{L.Calf}\ddot{Y}_{L.CalfCG} - F_{L.Ankle.Y} \qquad (B.155)$$

$$F_{L.Knee.Z} = m_{L.Calf}(\ddot{Z}_{L.CalfCG} + 9.81) - F_{L.Ankle.Z} \qquad (B.156)$$

The proximal (Prx) and distal (Dis) moment arms may be calculated as follows:

$$p_{Prx.4} = p_{L.Knee} - p_{L.CalfCG} \qquad (B.157)$$

and

$$p_{Dis.4} = p_{L.Ankle} - p_{L.CalfCG} \qquad (B.158)$$

where the subscript 4 refers to the left calf. The residual (Res) moment acting on the left calf is

$$\mathbf{M}_{Res.4} = -\,\mathbf{M}_{L.Ankle} - (p_{Dis.4} \times \mathbf{F}_{L.Ankle}) \qquad (B.159)$$
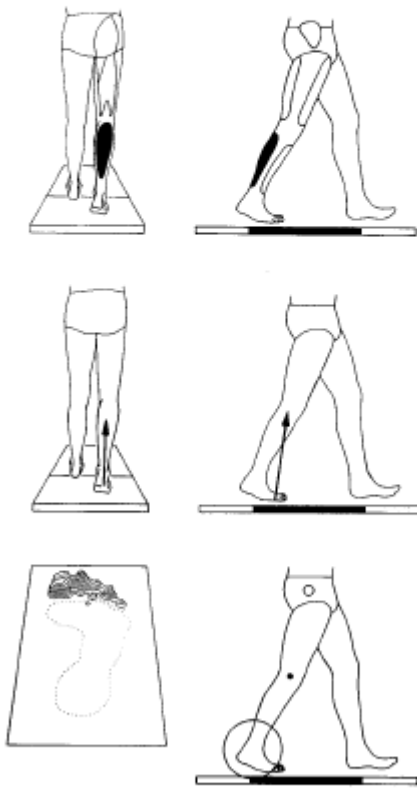$$+ (p_{Prx.4} \times \mathbf{F}_{L.Knee})$$

The rate of change of angular momentum for the left calf may be calculated using the standardised form of Equations B.82 to B.84. Then, application of the angular analogue of Newton's second law yields the following:

$$M_{L.Knee.x} = \dot{H}_{4x} - \mathbf{i}_4 \cdot \mathbf{M}_{Res4} \qquad (B.160)$$

$$M_{L.Knee.y} = \dot{H}_{4y} - \mathbf{j}_4 \cdot \mathbf{M}_{Res4} \qquad (B.161)$$

$$M_{L.Knee.z} = \dot{H}_{4z} - \mathbf{k}_4 \cdot \mathbf{M}_{Res4} \qquad (B.162)$$

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Adding these components gives

$$\mathbf{M}_{L.Knee} = M_{L.Knee.x}\,\mathbf{i}_4 + M_{L.Knee.y}\,\mathbf{j}_4 \qquad (B.163)$$
$$+ M_{L.Knee.z}\,\mathbf{k}_4$$

We can express the resultant joint force (**F**; Equations B.154 to B.156) and resultant joint moment (**M**; Equation B.163) in terms of a body-based coordinate system:

$$F_{L.Knee.PrxDis} = \mathbf{F}_{L.Knee} \bullet \mathbf{i}_4 \qquad (B.164)$$

$$F_{L.Knee.MedLat} = -\mathbf{F}_{L.Knee} \bullet \mathbf{k}_2 \qquad (B.165)$$

$$F_{L.Knee.AntPos} = \mathbf{F}_{L.Knee} \bullet \mathbf{l}_{L.Knee} \qquad (B.166)$$

Also,

$$M_{L.Knee.IntExt} = -\mathbf{M}_{L.Knee} \bullet \mathbf{i}_4 \qquad (B.167)$$

$$M_{L.Knee.FlxExt} = \mathbf{M}_{L.Knee} \bullet \mathbf{k}_2 \qquad (B.168)$$

$$M_{L.Knee.AbdAdd} = \mathbf{M}_{L.Knee} \bullet \mathbf{l}_{L.Knee} \qquad (B.169)$$

Left Thigh. Application of the linear form of Newton's second law to the left thigh yields the following:

$$F_{L.Hip.X} = m_{L.Thigh}\ddot{X}_{L.Thigh.CG} - F_{L.Knee.X} \qquad (B.170)$$

$$F_{L.Hip.Y} = m_{L.Thigh}\ddot{Y}_{L.Thigh.CG} - F_{L.Knee.Y} \qquad (B.171)$$

$$F_{L.Hip.Z} = m_{L.Thigh}(\ddot{Z}_{L.Thigh.CG} + 9.81) - F_{L.Knee.Z} \qquad (B.172)$$

The proximal (Prx) and distal (Dis) moment arms may be calculated as follows:

$$p_{Prx.2} = p_{L.Hip} - p_{L.Thigh.CG} \qquad (B.173)$$

and

$$p_{Dis.2} = p_{L.Knee} - p_{L.Thigh.CG} \qquad (B.174)$$

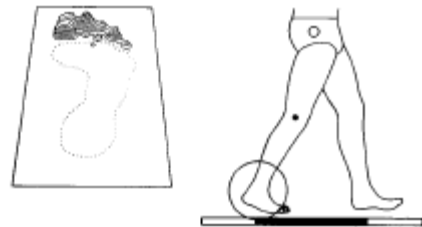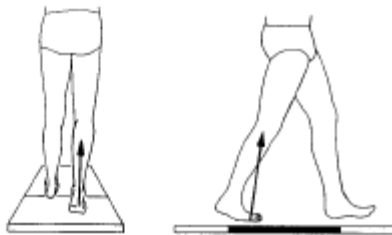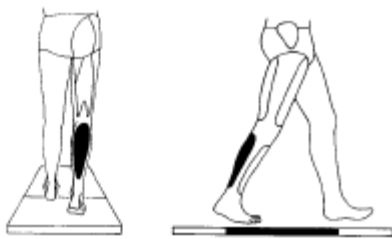where the subscript 2 refers to the left thigh. The residual (Res) moment acting on the left thigh is
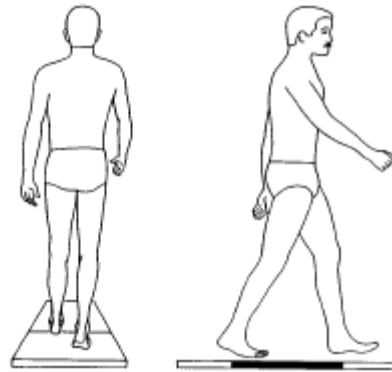
$$\mathbf{M}_{Res.2} = -\mathbf{M}_{L.Knee} - (p_{Dis.2} \times \mathbf{F}_{L.Knee}) \qquad (B.175)$$
$$+ (p_{Prx.2} \times \mathbf{F}_{L.Hip})$$

The rate of change of angular momentum for the left thigh may be calculated using the standardised form of Equations B.82 to B.84. Then, application of the angular analogue of Newton's second law yields the following:
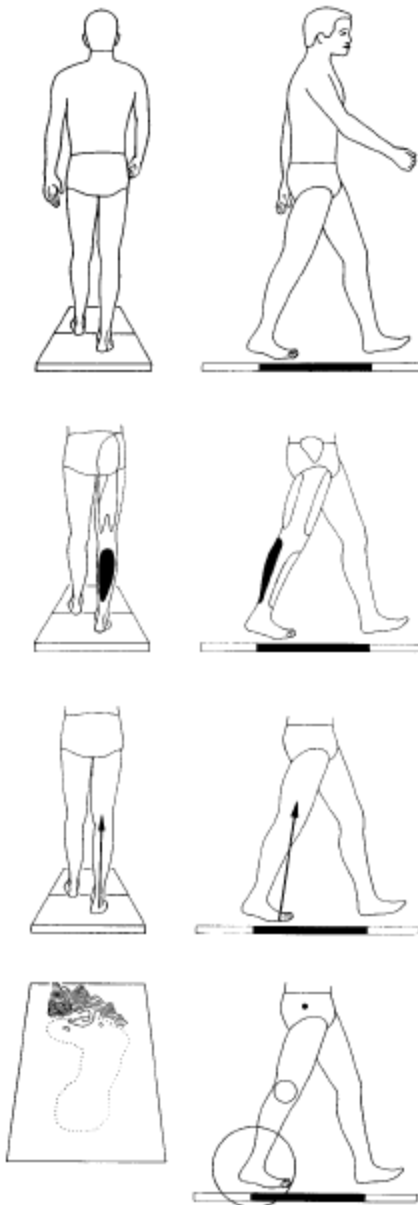
$$M_{L.Hip.x} = \dot{H}_{2x} - \mathbf{i}_2 \bullet \mathbf{M}_{Res2} \qquad (B.176)$$

$$M_{L.Hip.y} = \dot{H}_{2y} - \mathbf{j}_2 \bullet \mathbf{M}_{Res2} \qquad (B.177)$$

$$M_{L.Hip.z} = \dot{H}_{2z} - \mathbf{k}_2 \bullet \mathbf{M}_{Res2} \qquad (B.178)$$

Frame = 15
Time = 0.56 s
Right heel-off

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Adding these components gives

$$\mathbf{M}_{L.Hip} = M_{L.Hip.x}\,\mathbf{i}_2 + M_{L.Hip.y}\,\mathbf{j}_2 + M_{L.Hip.z}\,\mathbf{k}_2 \tag{B.129}$$

Again, we can express the resultant joint force ($\mathbf{F}$; Equations B.170 to B.172) and resultant joint moment ($\mathbf{M}$; Equation B.179) in terms of a body-based coordinate system:

$$F_{L.Hip.ProxDis} = \mathbf{F}_{L.Hip} \cdot \mathbf{i}_2 \tag{B.180}$$

$$F_{L.Hip.MedLat} = -\,\mathbf{F}_{L.Hip} \cdot \mathbf{k}_{Pelvis} \tag{B.181}$$

$$F_{L.Hip.AntPos} = \mathbf{F}_{L.Hip} \cdot \mathbf{l}_{L.Hip} \tag{B.182}$$

Also,

$$M_{L.Hip.IntExt} = -\,\mathbf{M}_{L.Hip} \cdot \mathbf{i}_2 \tag{B.183}$$

$$M_{L.Hip.FlxExt} = -\,\mathbf{M}_{L.Hip} \cdot \mathbf{k}_{Pelvis} \tag{B.184}$$

$$M_{L.Hip.AbdAdd} = \mathbf{M}_{L.Hip} \cdot \mathbf{l}_{L.Hip} \tag{B.185}$$

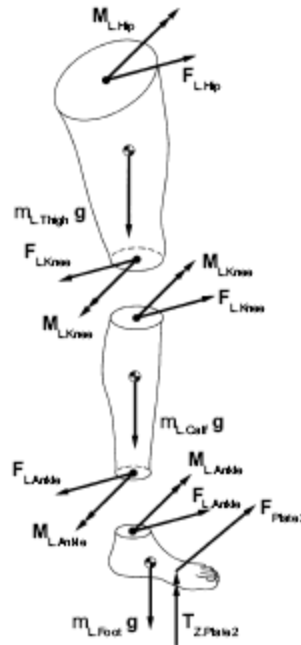See the left leg free body diagrams in Figure B.4.

Figure B.4 Free body diagrams for the left foot, calf, and thigh, showing the external forces acting on each segment. The forces and moments at the ankle and knee joints are equal in magnitude but opposite in direction, depending on the segment concerned (Newton's third law of motion).

Frame = 14
Time = 0.52 s

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