Fall 2013

Training strategies to reduce knee hyperextension gait patterns in healthy women

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Recommended Citation

Teran-Yengle, Patricia Cecilia. "Training strategies to reduce knee hyperextension gait patterns in healthy women." PhD (Doctor of Philosophy) thesis, University of Iowa, 2013.
https://doi.org/10.17077/etd.lw6jrxlz

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TRAINING STRATEGIES TO REDUCE KNEE HYPEREXTENSION GAIT PATTERNS IN HEALTHY WOMEN

by

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A thesis submitted in partial fulfillment of the requirements
for the Doctor of Philosophy degree in
Physical Rehabilitation Science
in the Graduate College of The University of Iowa

December 2013

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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ACKNOWLEDGMENTS

Thanks to: my wonderful parents for their love, support, and constant encouragement; Dr. Gabriele Wulf, Dr. Kelly Cole, and my thesis committee members for their guidance, discussion, and feedback through the development of my dissertation work; Bhupinder, Shacoya, Jessica, and all my fellow graduate students who helped me with data collection. I am very grateful to all of you.

My sincere gratitude to Dr. John Yack for his outstanding mentorship and unconditional support. Dr. Yack has set an example of excellence as a researcher, mentor, instructor, and role model. There are not enough words to express my gratitude to him.

Thank you God for giving me the strength to pursue my dreams.

To my beloved brother Carlos, who encouraged me to pursue my PhD degree.

ABSTRACT

Clinicians working on motor skill learning interventions often find that improvements observed during training are not sustained and do not transfer to very similar tasks. Research suggests that strategies such as real-time biofeedback and learner's focus of attention seem to facilitate motor skill learning. However, research on the implications of these strategies in rehabilitation is limited and has not been investigated in healthy individuals. The motor learning effects of these strategies need to be assessed as they offer the possibility of enhancing rehabilitation regimens. The purpose of this study was to investigate the generalizability of real-time biofeedback and learner's focus of attention to a treadmill gait retraining program aimed at correcting knee hyperextension insidious gait patterns in healthy young women. Assessing the acquisition, retention, and transfer of kinematic improvements was the focus of this study.

1. Knee sagittal plane kinematics could be influenced with dynamic gait training using real-time biofeedback. Gained proficiency in controlling knee hyperextension during treadmill training was evident during overground walking immediately and 1 month after training.
2. The effectiveness of real-time biofeedback in improving performance does not seem to be influenced by the focus of attention, internal or external, induced during treadmill training. Participants in both intervention groups improved in a similar way as a consequence of practice. However, there were trends in the data that pointed that the external focus of attention group had better long-term retention. It is not known if participants actively switched to an external focus of attention despite the instructions provided during training. Tests to ensure instructional compliance should be used.
3. A treadmill gait retraining program using learner's focus of attention indicated that that there were not differences in learning acquisition, short and long-term

retention, and transfer to overground walking and obstacle crossing between intervention groups. It is not known if these changes persist beyond the 4-month follow-up included in this study.

The results of this study will help to reduce knee hyperextension gait patterns in women. Future studies may also use the methodology used in this study to further investigate the implications of learner's focus of attention in rehabilitation. Similarly, the findings of this study could offer an additional strategy for rehabilitation regimens.

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INTRODUCTION

Clinicians working on interventions that require learning or modifying motor skills often find that improvements observed during training are not sustained and do not transfer to similar tasks (1). How well skills are retained over time (retention) and how well they can be used in new situations the learner may encounter (transfer) are important concerns in motor learning as both, retention and transfer, are indicators of relatively permanent changes in the capability of movement (2). Therefore, there is a need to find strategies that facilitate effective learning. Research in motor control and learning suggests that augmented kinematic feedback (3) and strategies that manipulate the focus of attention of the learner (4-6) may influence learning of motor skills. However, research on the implications of these strategies in rehabilitation has not been investigated.

The impact of augmented feedback on learning appears to be greatest when it precisely specifies information that is critical for movement efficiency and that cannot be obtained from other sources of feedback (3). Research has suggested that instructions that direct the learner's attention to his or her own movements can actually have a detrimental effect on learning and disrupt the execution of automatic skills, particularly in comparison with an externally directed attentional focus (4-6). The exact reasons for the beneficial effects of an external focus of attention are still unclear. However, trying to consciously control one's movements might interfere with the normal, automatic motor control processes, leading to a breakdown in the natural coordination of the movement (4-6). The effects of learner's focus of attention have been investigated mostly in sports related tasks, in a context that emphasizes the outcome, and have not been investigated in motor skills that clinicians typically work on, which typically emphasize the production of specific movement forms. The implications of augmented kinematic feedback and learner's focus of attention instructions in rehabilitation need to be assessed as they offer the possibility of enhancing intervention regimens.

The effects of augmented kinematic feedback and learner's focus of attention instructions will be investigated relative to each aspect of motor learning (acquisition, retention, and transfer) in an effort to teach healthy women with knee hyperextension to avoid knee hyperextension during gait activities. Methods to correct for knee hyperextension, an insidious condition that mostly affects women, have typically concentrated on awareness of the joint's position through taping, bracing, muscle strengthening, and verbal feedback. These methods, which are biased to an internal focus of attention, have shown limited success. Intervention strategies that lead to permanent control of knee joint sagittal alignment in women with knee hyperextension are needed as this condition can precipitate catastrophic knee events or, in the long term, contribute to abnormal accumulated knee stressors resulting in pathology.

Motor Skill Learning

Learners appear to pass through relative distinct phases when acquiring a motor skill (7). According this theory, during the initial phase, learners have to find out the correct movement by trial and error. During this *cognitive phase*, the learner's major goal is the establishment of perceived sensory cues with the correct motor commands. The *associative phase* begins when the learner has determined the most effective way of doing the task and starts to make more subtle adjustments in how the skill is performed. After days, weeks, or months of practice (depending on the skill), the learner enters the *autonomous phase*. The task can now be performed with less intensive sensory feedback processing, movements become automatic and can be performed at high speed and accurately, even if learners do not attend the action (2, 7). The learning process will ultimately be demonstrated by the increased proficiency in the task.

Given that motor learning is a set of processes that underlie changes in the capability of movement, the assessment of effective motor learning strategies requires observation and measurement of permanent changes. Motor learning has been defined as "a set of processes associated with practice or experience leading to relatively permanent changes in the capability of movement" (2). Thus, to assess if a skill has been learned there is need to measure the relatively permanent changes in the capability of movement. To do this, researchers use transfer and retention tests. Tests involving the same task as practiced in the acquisition phase are called retention test, as they evaluate the extent to which a given task has been retained over time. Transfer is defined as the gain in the capability for performance in one task as a result of practice or experience on some other task (8). Then, transfer tests typically involve new variations of the task practiced in acquisition or might involve essentially new tasks that have not been practiced before (8). Both, retention and transfer tests help to separate between temporary effects and the relatively permanent effects due to learning.

In summary, one of the most important objectives in motor skill learning is to ensure that once skills are learned, they are retained (retention) so that they can be used in new situations (transfer). Motor learning research has suggested that factors such as augmented feedback and directing the learner's focus of attention might enhance the learning of motor skills (9). The implications of these factors in rehabilitation have not been investigated.

Augmented Feedback

Augmented feedback is information provided about the task that is supplemental to, or augments, the inherent or intrinsic feedback (from the moving limbs, audition, vision, etc.) (3). Augmented feedback can be delivered in different ways, such as verbal descriptions and demonstrations, auditory sources, visual displays, and biofeedback (physiological measures concurrently fed back to the learner through some form of instrumentation) (10). Augmented feedback is utilized to provide learners with information about the outcome (knowledge of results) or the quality of the movement (knowledge of performance). Knowledge of performance can be given through video feedback, recordings of the force-time characteristics of the movement (kinetics), or representations of the movement trajectories (kinematics) (3, 11).

Augmented feedback appears to facilitate motor skill learning (12, 13); however it seems to create dependency when presented too often. The impact of augmented feedback on learning appears to be best when it precisely specifies information that is critical for movement efficiency and that cannot be obtained from other sources of feedback (3). In addition to providing specific information about the movement, augmented feedback also improves learner's motivation and optimizes error correction (10). Research has also shown that augmented feedback presented too often can create dependency that could prevent the learner from developing error detection mechanisms, therefore interfering with an effective permanent learning (11, 14-17). Researchers are still trying to elucidate the amount of augmented feedback required to facilitate learning while not creating a dependency on the feedback (18, 19).

Human movement studies have shown that a key feature of knowledge of performance is that it informs the learner about some aspect of the movement of a particular joint and/or a whole pattern of multijoint coordinated motion that is otherwise difficult to perceive. The use of kinematic or kinetic feedback, with specific output measures provided to the subject in real time, has been shown to enable individuals without neurological impairments to make subtle changes to their gait patterns (20-22). The results of these studies showed positive effects immediately after training, only Noehren and colleagues included 1-month retention test (22). Additional studies are needed to assess the long-term success of kinematic real-time feedback.

Learner's Focus of Attention Instructions

Research suggests that the learner's specific attentional orientation can have an important influence on learning motor skills (6, 9, 23). Clinicians' instructions typically seek to simplify a task and are often geared toward directing the patient's attention to various components of the skill. The subtleties involved in providing instructions may not consider how the instructions affect the patient's focus of attention (24). Research has suggested that instructions that direct learner's attention to his or her own movements can actually have a detrimental effect on learning and disrupt the execution of automatic skills, particularly in comparison with an externally directed attentional focus. Therefore, the effectiveness of clinicians' instructions could potentially be enhanced by manipulating the instructions to induce a specific focus of attention.

Key Findings of Attentional Foci Research

Views about where to optimally focus our attention during an action have been postulated since the late 18th century. In his discourse on which aspects of intended actions are functional in action control, James (25) pointed out that the distant result of the action (*referred as remote effects*) are often more important than the action itself (*referred as close effects*). For example, James stated: "Keep your eye at the place aimed at, and your hand will fetch; think of your hand and you will likely miss your aim" (James, 1890). Later in 1940, James Cattell's work on attention addressed the issue of attentional focus by pointing out that "In the practiced automatic movements of daily life attention is directed to the sense impression and not to the movement" and focusing on the movement itself would make the movement to "become less automatic and less dependable" (26). These early thoughts on the effects of self-attention on the performance of motor skills laid the foundation for empirical research.

Motor learning research in attentional focus seems to corroborate the accuracy of early anecdotal observations. According to Henry and Rogers' work (27), attempts to consciously control well-learned movements interfere with performance. The result of this interference is an increase in reaction time when the performer is asked to concentrate on the "to-be-performed" movement (*referred as enforced motor set*), as opposed to concentrating on the stimulus that evokes the response (*referred as enforced sensory set*) (27). Henry and Rogers' finding was supported by Henry (28) and Christina (29). Although the learning effect was not assessed, these studies advocate that concentrating on the outcome of the action can be more effective than concentrating on the movement itself.

The effects of attentional focus have also been suggested to influence the learning of motor skills. Singer et al (30) had participants practice a ball-throwing task under different learning strategies. Singer et al. found (30) that when learners perform the task without consciously attending to its movement pattern (*nonawareness strategy*) they produced a more effective performance during acquisition and in a dual-task transfer test than when learners consciously attend to the movement (*awareness strategy*). Consistent with Singer's finding, Wulf et al. (23) showed that providing learners with instructions that direct their attention on the wheels of the ski-simulator (*external focus*) was more effective for learning ski-type slalom movements on a ski-simulator than directing their attention to their feet (*internal focus*). Wulf et al. (23) suggested that instructions related to the learner's body movement, referred as *internal focus*, might not be as optimal for learning as instructions that have the same goal but direct the learner's attention away from their own movements, for example to the effects that those movements have on the environment, or sporting equipment, referred as *external focus*. These findings have since been replicated several times by Dr. Wulf and her colleagues, using tasks like balance (5, 31-38), tennis strokes (39), hitting golf balls (40, 41), serving volleyballs and passing soccer balls (42), and postural stability in older individuals with Parkinson Disease (43). Some studies, however, have reported no differential effects of attentional focus (44, 45) or suggested that the effects of focus of attention may depend on the learner's skill (46).

The finding that external focus instruction, relative to internal focus and no instructions, enhances retention of motor skills has been recently challenged. After having the internal and external focus of attention groups perform a balancing task in a wobble board, Maxwell and Masters (44) found no differential effects of attentional focus during learning and retention. Consistent with Maxwell and Master's findings, Poolton et al (45) reported no learning advantages in the external focus of attention group using a golf putting task. These results suggested differences in the experimental protocols as in most of Dr. Wulf's studies the retention tests were conducted a day after the completion of the learning trials. In addition, these findings suggest the possibility that participants may have not adhered to specific instructional constraints as instructional compliance has been hard to prove in some studies. Thus, manipulation tests should be included in future studies to assess participants' instructional compliance.

Studies have also suggested that the effects of focus of attention may depend on the learner's skill. Using a golf pitching task, Perkins-Ceccato et al. (46) reported that while experts' performances were superior under external focus conditions, novice golfers performed better under internal focus instructions. Perkins-Ceccato and colleagues suggested that in golf pitching tasks, once the fundamentals of the swing have been learned well, performance will benefit more by using an external focus of attention (e.g. where to hit the shot). On the other hand, low-skill golfers may benefit from concentrating on the mechanics of the task (e.g. force production). The results of Perkins-Ceccato's study (46) support James's (25) early observations that the "remote effects" of an action (currently referred to as external focus) is beneficial only for skills that are well learned. In addition, the results of these studies suggest that although participants in many studies assessing the effects of focus of attention have been categorized as novice, the task performed may not have been completely novel to them or that participants were assumed to be novice at the beginning of the studies and were familiarized with the task at the initial stage of the studies (47). Thus, the use of a novel task is needed to minimize the potential impact of learners' past experiences on the acquisition of a skill.

Theoretical Explanations for Focus of Attention Strategies

The advantages associated with an external focus of attention seem to arise as a consequence of the utilization of a more unconscious or automatic processes, whereas an internal focus of attention may result in a more conscious type of control that constrains the motor system and disrupts automatic control processes. The focus of attention strategies evolved from the common coding principle (48) which proposes that a high degree of compatibility between afferent and efferent information is needed to produce effective actions. Then, movements need to be arranged in terms of their outcome or effect (48). An external focus of attention may lead to a more effective learning process by facilitating movement automaticity and promoting the utilization of unconscious or automatic processes and promoting the utilization of more natural control mechanisms (5, 6). In addition, an external focus of attention has been suggested to enhance a more efficient and effective movement as a result of reduced electromyographic (EMG) activity (49, 50) and greater force production (51). In contrast, an internal focus may interfere with performers' normal motor system and automatic control of movement (constrained action hypothesis) by increasing self-consciousness and active self-regulatory processes in attempts to control their movements (5, 6). Further research is needed to elucidate the exact reasons for the beneficial effects of an external focus of attention.

Implications of Learner's Focus of Attention in Rehabilitation

Despite the considerable attention given to internal versus external focus of attention in motor learning studies, research assessing the implications of learner's focus of attention in rehabilitation is limited (43, 52). The effect of instructions which bias the focus of attention instructions in clinical applications needs to be investigated as it offers the possibility of enhancing rehabilitation and training regimens. Some of the activities that clinicians typically work on (related to developing the patient's range of motion, flexibility, muscle force or endurance) emphasize the production of specific movement forms and often involve instructing patients to focus on the body segment under treatment (internal focus of attention) rather than instructing patients to focus on a movement-related cue outside of the patient's body (external focus of attention). For example, if the goal is to increase the step length of a patient, instructing the patient to fully extend the knee and flex the hip (internal focus) might not be as effective as instructing the patient to move a walker or cane further ahead (external focus). Although many physical therapists may be familiar with these techniques, the rationale and implications of using particular instructions may not be appreciated and has not been researched (53).

Definition of Internal and External Focus of Attention

Since the learner's attentional orientation was proposed in 1890, researchers have used different terminology to define similar concepts. James (25) originally used the terms "*close and remote effects*" to refer to the action itself and to the distant result of the action, respectively. Later, Henry and Rogers (28) used "*enforced motor set and enforced sensory set*" to refer to the movement to be performed and to the stimulus that evokes the movement, respectively. Similarly, Singer et al. (30) used the terminology "*nonawareness strategy*" to describe the condition in which learners perform the task without consciously attending to its movement pattern and "*awareness strategy*" to describe the condition in which learners consciously attend to the movement. In the same way, to study the effects of attentional focus mainly in sports related activities, Dr. Wulf and colleagues (23) for the first time used the term "*internal focus*" to refer to instructions related to the learner's body movements and "*external focus*" to refer to instructions that have the same goal but direct the learner's attention away from their own movements to the effects that those movements have on the environment, or sport equipment.

While the definition of what is currently known as "internal focus" has involved various instructions related to the learner's body movements, the definition of "external focus" appears to be more variable and could leave room for ambiguity as to what other motor skills might also be relevant. The terms "*close effects*" (25), "*enforced motor set*" (28), "*awareness strategy*" (30), and currently "*internal focus*" (23) have consistently been used to refer to actions or instructions related to conscious awareness of the learner's body movements. On the other hand, the terminology "*remote effects*" (25), "*enforced sensory set*" (28), "non*awareness strategy*" (30), and "*external focus*" (23) have been used to refer to the distant result of the action, stimulus that evokes the movement, no attention to the movement, and instructions that direct the learner's attention away from their own movements to the effects that those movements have on the environment, or sport equipment, respectively.

Despite of the lack of consistency, definitions of what is currently known as "external focus" seem to agree that the learner's attention needs to be away from their own movements. A point of disagreement seems to be where the learner should focus their attention. Most of the studies addressing learner's focus of attention have used sport related skills that involve the use of an object in the environment (e.g. club, ball, moving surface, or racket). The presence of an object might have made it easy for the learner to focus on the object or movement effect on the object and may also explain the definition given to "external focus" by Dr. Wulf and colleagues (e.g. effects that movements have on the environment, or sport equipment). However, there are skills that may not involve the use of an object (e.g. dance). Thus, the current definition does not seem to apply to these types of motor skills. In such cases, Dr. Wulf has suggested the use of analogies or metaphors that ultimately will tend to distract the learner's attention from their body movements and would also provide a mental image of the movement goal (6). Consistent with previous definitions of an "external focus", Dr. Wulf's suggestion corroborates the need for the focus of attention to be oriented away from the learner's body and instead to be oriented to the end result of the movement. The development of operational definitions will prevent ambiguities and enable the investigation of the effects of attentional focus instructions in motor skills that clinicians typically work on (e.g. improvement of patient's range of motion, flexibility, muscle force or endurance).

Knee Hyperextension

The paradigm that will be used to explore the aforementioned motor learning issues is modifying knee range of motion during gait, to prevent knee hyperextension. Abnormal knee arthrokinematics can result in excessive loading of structures of the knee joint, such as menisci, ligaments, or cartilage. Associated change to these structures, due to the abnormal stress, can be detrimental to the integrity of the knee joint (54-57). Normal standing posture of the knee in the sagittal plane consists of a vertically aligned femur and tibia, forming a 180 degrees angle. Movement of the knee into hyperextension (genu recurvatum) of more than 5° is associated with a ground reaction force vector that acts anterior to the knee joint, placing substantial increased stress on the passive restraining structures that resist further knee extension.

Knee hyperextension implies increased stress to the posterior joint capsule of the knee and to the anterior cruciate ligament (ACL) (58), increased contact stress on the anterior compartment of the tibiofemoral joint (59), and has been identified as one factor related to the increased injury and cartilage degeneration (60-62). When tracking the motions of the knee under laboratory-controlled knee joint hyperextension experiments in human cadaver joints, high contact pressures were noted in the anterior compartment of the tibiofemoral joint due to the combined rolling and sliding of the femoral condyles on the anterior tibial plateau during hyperextension (63). Several studies have reported that compared with men, women demonstrated more genu recurvatum (60, 64-66). Female athletes with knee hyperextension are 5 times more likely to injure their anterior cruciate ligament (ACL) (62). A study conducted by our group to investigate knee joint sagittal plane kinematics during functional activities in women with asymptomatic knee hyperextension showed that the magnitude of knee hyperextension seen at PROM was not different than during most of the activities assessed. In addition, level and decline walking were the activities that were most associated with knee hyperextension (Appendix Chapter).

Attempts at controlling hyperextension using various approaches, such as taping (64), bracing (67), and muscle strengthening (64), have shown limited success. Noyes (68) showed positive post-intervention results when training (using verbal feedback) 5 patients with symptomatic knee hyperextension to avoid knee pattern by maintaining their knees slightly flexed, ankle dorsiflexed, and trunk-hip erect during stance phase of walking. While some of these approaches produce short-term improvement, patient compliance and the ability of these interventions to affect the underlying motor pattern limit long-term benefits. Intervention strategies that lead to permanent control of knee joint sagittal alignment in women with knee hyperextension are needed as this condition can precipitate catastrophic knee events or, in the long term, contribute to abnormal accumulated knee stressors resulting in pathology.

Operational Definitions

AUGMENTED FEEDBACK: Information provided to supplement intrinsic feedback. Specifically in this study participants will receive augmented feedback in the forms of verbal instructions and visual display. Verbal feedback will be used to reinforce attentional focus instructions. Visual feedback will be used to provide a visual image of the movement goal.

INTERNAL FOCUS OF ATTENTION: Attention directed to the learner's body movements. For the purpose of this study, internal focus of attention will be defined as the attention directed to participants' knee joint.

EXTERNAL FOCUS OF ATTENTION: Attention oriented away from the learner's body and instead oriented to the end result of the movement. For the purpose of this study, external focus of attention will be defined as attention oriented to an external cue (alignment angle of wands placed on participants' lower limbs). External cues will distract the learner's attention from their body movements and will also provide a mental image of the movement goal.

RETENTION: Extent to which a given task is maintained over time. Specifically, retention will be defined as the ability to maintain the improved control of the knee joint sagittal alignment approximately one week (short-term retention) and one, four, and eight months (long-term retention) after training.

TRANSFER: Gain in the capability for performance in one task as a result of practice or experience on some other task. Specifically, transfer will be defined as the improvement in controlling knee hyperextension during overground walking (same activity performed in a different environment), and obstacle crossing (untrained activity performed in a different environment) as a result of practice controlling knee joint sagittal alignment during treadmill walking.

Purpose

The purpose of this study is to investigate acquisition, retention, and transfer effects of a treadmill gait retraining program using augmented kinematic feedback and learner's focus of attention aimed at correcting knee hyperextension insidious gait patterns in healthy young women.

Specific Aims

The purpose of this study will be attained by pursuing the following specific aims in Chapters 2, 3, and 4, respectively:

Specific Aim 1 (Chapter 2): To investigate the efficacy of a treadmill gait training program using real-time kinematic feedback for correcting knee hyperextension in asymptomatic females.

1.a. To determine performance effect during acquisition phase of treadmill gait retraining program using real-time biofeedback.

1.b. To establish short-term (2 days after training) and long-term (1-month after training) retention effect of treadmill gait training program using real-time biofeedback.

Specific Aim 2 (Chapter 3): To examine if an external or internal focus of attention influenced the effectiveness of real-time visual biofeedback, during treadmill gait training for correcting knee hyperextension patterns, in young, asymptomatic, female subjects.

2.a. To compare performance during acquisition phase of treadmill retraining program as a function of external and internal focus of attention.

2.b. To compare short-term (2 days after training) and long-term (1-month and 8-months after training) retention effects of training program as a function of external and internal focus of attention.

Specific Aim 3 (Chapter 4): To investigate the efficacy of a treadmill gait retraining program using learner's focus of attention instructions in correcting knee hyperextension in asymptomatic females.

3.a. To assess learning acquisition as a function of learner's focus of attention.

3.b. To establish short-term (2 days after training) and long-term (4 months after training) retention as a function of learner's focus of attention.

3.c. To assess transfer effects of a treadmill retraining program using learner's focus of attention to overground walking and obstacle crossing.

Hypotheses and Rationale

The hypotheses for the specific aims mentioned above are as follows:

Chapter 2: Efficacy of Gait Training with Real-time Biofeedback.

Hypothesis 1a:

Treadmill training using real-time feedback will facilitate the reduction of knee hyperextension during the acquisition phase.

Hypothesis 1b:

Treadmill training using real-time feedback will lead to improved control of knee hyperextension immediately following training and at a 1-month follow-up.

Rationale: The use of real-time feedback, with specific output measures provided to the subjects in real time, has been shown to enable individuals to make subtle changes to their gait patterns, such as in patients following total hip arthroplasty (20), runners with high peak positive acceleration of the tibia (21), and runners with patellofemoral pain syndrome (22). We hypothesize that real-time kinematic feedback will lead to improved control of knee hyperextension during the acquisition phase. Gained proficiency in controlling knee hyperextension patterns will also be evident 2 days (short-term) and 1-month (long-term) retention tests.

<u>Chapter 3: Effects of Learners' Focus of Attention Instructions and Biofeedback</u>

Hypothesis 2a:

Receiving treadmill gait training, with real-time biofeedback, will be more effective in improving performance during acquisition when the focus of attention is external rather than internal.

Hypothesis 2b:

Participants in the external focus of attention group will show a better long-term retention of performance gains compared to participant in the internal focus of attention group.

Rationale: Previous study assessing attentional focus of attention (31) have suggested that the augmented visual feedback provided to learners during practice can be more effective if it directs attention to the effects of the movement (external focus of attention) instead of to the movement itself (internal focus). We hypothesize that receiving treadmill gait training, with real-time biofeedback; will be more effective in improving acquisition and retention when the focus of attention is external rather than internal.

<u>Chapter 4: Learning Effects of a Training Program Using Learner's Focus of Attention Instructions to Correct Knee Hyperextension Gait Patterns in Young Women</u>

Hypothesis 3a:

Women in the external focus of attention group will demonstrate a greater acquisition of learning than women in the internal focus of attention group.

Hypothesis 3b:

Women in the external focus of attention group will demonstrate greater short and long-term retention than women in the internal focus of attention group.

Hypothesis 3c:

Women in the external focus of attention group will demonstrate greater percentage of transfer to untrained tasks than women in the internal focus of attention group.

Rationale: Research has suggested that trying to consciously control one's movements constrains the motor system by interfering with automatic control processes that would normally regulate the movement. Focusing on an external cue, on the other hand, would lead to more effective learning by promoting the utilization of automatic and natural control mechanisms instead of self-regulatory processes in attempts to control one's movements (5, 23, 35). In addition, an external focus of attention would enhance a more efficient and effective movement (49, 50), and facilitate a more effective coordination pattern translated into a lower level of cocontraction (51). By promoting automaticity of movement control during treadmill gait retraining program, women in the external focus of attention group would be able to control tibiofemoral sagittal alignment using strategies that might be less affected by conditions that differ from those under which the skill was practiced. Then, the improved alignment could be retained overtime and transferred to untrained tasks performed in a different environment.

CHAPTER 2

EFFICACY OF GAIT TRAINING WITH REAL-TIME BIOFEEDBACK IN CORRECTING KNEE HYPEREXTENSION PATTERNS IN YOUNG WOMEN

Introduction

Knee hyperextension is an insidious condition that has a greater incidence in women than in men (60, 65, 69). Women who hyperextend their knees are generally asymptomatic; however, knee hyperextension can precipitate catastrophic knee events or, in the long term, contribute to abnormal accumulated knee stressors resulting in pathology. Female athletes with knee hyperextension are 5 times more likely to injure their anterior cruciate ligament (ACL) (62). In addition, knee hyperextension has been associated with increased stress to the posterior capsule of the knee (64, 70) and anterior compartment of the tibiofemoral joint (59) which can be detrimental to the integrity of the joint (54-56, 71).

Knee hyperextension is typically associated with weight-bearing activities. In a normal standing posture, with the femur and tibia vertically aligned, the tibiofemoral joint typically is in near vertical alignment defined anatomically as 0°. Movement of the knee into hyperextension (genu recurvatum) of more than 5° is associated with a ground reaction force vector that acts anterior to the knee joint, placing substantial increased stress on the passive restraining structures that resist further knee extension.

Conventional attempts to control knee hyperextension during ambulation, such as bracing (67), taping (64), and muscle strengthening (64) have had limited success. While some of these approaches produce short-term improvement, patient compliance and the ability of these interventions to affect the underlying motor pattern limit long-term benefits.

Augmented feedback has been shown to facilitate the acquisition of skilled motor performance and to contribute to generalized or transferable learning (3, 10, 72, 73).

Noyes and associates (68) explored the use of verbal feedback in individuals with knee hyperextension and reported overcorrected patterns during terminal stance. However, the use of real-time feedback, with specific output measures provided to the subject in real time, has been shown to enable individuals to make subtle changes to their gait patterns, such as in patients following total hip arthroplasty (20), runners with high peak positive acceleration of the tibia (21), and runners with patellofemoral pain syndrome (22).

The purpose of this study was to investigate the efficacy of real-time biofeedback for correcting knee hyperextension in asymptomatic females during walking. It was hypothesized that receiving treadmill training using real-time feedback would lead to improved control of knee hyperextension during overground walking, immediately following training and at a 1-month follow-up.

Methods

Subjects

Ten healthy women (mean +/- SD age, 26.2 +/- 5.4; mass, 71 +/- 14 kg; height, 1.6 +/- 0.1 m) with no history of lower limb surgery or cardiovascular, functional or visual limitations took part in this study. Participants were screened and included in the study if they had asymptomatic knee hyperextension greater than 5° during passive range of motion. Knee hyperextension was measured in supine with the ankle resting on a 10-cm support, using standard goniometric techniques. Prior to participation, all subjects provided informed consent and the study protocol was approved by the University of Iowa’s Institutional Review Board.

Testing Protocol

Overground gait evaluation was conducted along an 8-m walkway, with the subjects walking at a speed of 1.3 m/s. Walking speed was monitored using an overhead timing chain. The knee with the highest amount of hyperextension during passive range of motion or gait evaluations was defined as the involved knee and was the focus of the gait retraining intervention.

A 3-dimensional motion analysis system (Optotrak™, Northern Digital Inc., Waterloo, Ontario - Canada) was used to collect kinematic data during gait. Three non-collinear infrared markers were used to track each of the 7 segments: 2 feet, 2 legs, 2 thighs, and pelvis. Marker coordinate data were collected at 60 Hz and filtered at 6 Hz. To define the axes of each of the 7 segments, an anatomical model was created by digitizing standard bony landmarks: anterior and posterior superior iliac spines, greater trochanters, lateral and medial epicondyles lateral and medial malleoli, posterior heel, second toe, and the head of the fifth metatarsal. Kinematic data were calculated using Visual 3D (C-Motion, Germantown, MD). To increase intersession consistency in defining the axes of each segment a marking pen was used to place identifying marks over the greater trochanters, lateral epicondyles, and lateral malleoli and retouched at every training session. This modeling approach was used for the 3 overground data collections at pretraining, posttraining (a minimum of 2 days and maximum of 5 days following the sixth training session) and 1-month follow-up in which 5 walking trials were collected (4 full gait cycles were analyzed for each walking trial).

Training Protocol

Following the initial evaluation, subjects participated in supervised treadmill training twice a week for 3 weeks. The same modeling approach used for the 3 over-ground data collections was used for treadmill gait training, in which subjects were provided with knee kinematic data in real-time (Visual 3D). During the first treadmill training session, subjects watched a 3-minute educational presentation on the implications of knee hyperextension, which was created for this project, and were oriented to the real-time feedback system. During gait training, knee sagittal plane kinematics data for 3 previous gait cycles were provided on a computer screen, placed on a table (150 cm in height) about 1 m in front of the subjects (Figure 2.1). After participants practiced observing how changes in knee angle affected representations on the monitor, they began the training. Each training session lasted 1 hour and consisted of three 8-minute sub sessions, with 3-minute rest periods between sessions. During each 8-minute sub session, participants received verbal and real-time visual biofeedback from the second to the sixth minute. Participants were instructed to bend their knee, keep their joint angle within the target line (Figure 2.1), and try to maintain a normal gait pattern. Ten seconds of gait data, without feedback, were collected at the beginning and end of each treadmill training session.

Data Analysis

Descriptive statistics for age, height, weight, and passive range of motion were calculated. Sagittal plane peak knee extension values during overground walking for 5 gait cycles, with subjects walking at 1.3 m/s, collected on 3 occasions were analyzed. Comparisons of peak knee extension values for the involved knee at pretraining, posttraining, and 1-month follow-up were made using a 1-way repeated-measures analysis of variance (ANOVA). Significant results were explored using the Tukey Studentized range follow-up test ($p < 0.05$). All statistical testing was performed using SAS 9.2 (SAS Institute Inc., Cary, NC, USA). Missing data were calculated using an imputation technique, which minimizes the effect on the error mean square (74).

Results

Initial Evaluation

Mean +/- SD knee passive range of motion was 9.6º +/- 3.0º (range, 6° - 14°). Pretraining gait evaluations showed that 7 subjects had greater knee extension in their right knee. Maximum knee extension occurred at initial contact in 7 subjects and at toe-off in 3 subjects. Mean peak knee extension during gait was 8.7° +/- 3.3°.

Overground Data

All 10 subjects underwent pretraining and posttraining gait evaluations. Nine of the 10 subjects underwent a 1-month follow-up gait evaluation. Individual and mean values of peak knee extension in the involved knee during walking at pretraining, posttraining, and 1-month follow-up gait evaluations are presented in the Table 2.1.

The ANOVA indicated that there was a significant difference (P<.001) in knee hyperextension between the 3 testing sessions when walking overground at 1.3 m/s (Figure 2.2). Follow-up testing revealed that there was a significant reduction of knee hyperextension between pretraining to posttraining (mean of 9.9°, P<.05) and pretraining to 1-month follow-up (5°, P<.05). In addition, there was significant increase (4.7°, P<.05) in knee extension between posttraining and 1-month follow-up evaluations.

Discussion

The purpose of this study was to investigate the efficacy of real-time biofeedback provided during treadmill gait training for correcting knee hyperextension in otherwise healthy young female subjects while walking. It was hypothesized that subjects would demonstrate improvements in controlling knee hyperextension during overground walking at 1.3 m/s at posttraining and 1-month follow-up gait evaluations. The results of the present study show significant reductions in knee hyperextension patterns following training and at 1 month. These results suggest the ability of treadmill gait training with real-time feedback to modify the motor program and transfer learning to overground walking.

The criterion used to define knee hyperextension (greater than 5°) is consistent with that of previous studies and is greater than the mean of 1.6° (range, 1.1° - 2.1°) of passive knee extension that has been reported in normative data for female subjects, 20 to 44 years of age (75). In addition, the magnitude of knee hyperextension seen in our study (mean +/- SD passive range of motion, 9.6º +/- 3º; knee extension during overground gait, 8.7° +/- 3.3°) is similar to that previously reported in other studies of this population (7.3°+/- 4.4°) (68). In contrast to previous work, where knee hyperextension was noted at toe-off (68), the majority of subjects (7 of 10) in the current study had the greatest hyperextension at initial contact. Control of the knee at these 2 instants in the gait cycle is governed by different muscle groups. The knee flexors (hamstrings) slow the forward motion of the foot and leg segments at the end of the swing phase and initiate knee flexion at initial contact, responding to a ground reaction force vector that acts anterior to the knee. Inadequate control of the knee by the knee flexors could result in increased knee extension just prior to, and extending into, initial contact. Near toe-off, the flexion action of the gastrocnemius muscle typically counterbalances the anterior ground reaction force that is attempting to move the knee into hyperextension.

In a previous study, using verbal feedback with observational gait analysis, Noyes and associates (68) showed that the abnormal knee hyperextension pattern in 5 symptomatic patients changed to a knee flexion pattern (averaging 15° of flexion) following 2 to 4 training sessions. The change to a more flexed knee pattern is not necessarily a desirable outcome, as this pattern could potentially increase the demands on the quadriceps to stabilize the knee (76) and increase compression force at the patellofemoral joint. This overcorrection of the problem may be related to the difficulty in using observation and verbal feedback to try to correct dynamic activities. The results of the present study show that after the 6 sessions of treadmill gait retraining the knee maintained a more normal extension angle (+/- 5°) when walking over ground. The outcome of the present study helps validate the effectiveness of real-time kinematic biofeedback in informing individuals about specific and subtle aspects of the movement pattern that would otherwise be difficult to perceive and appropriately correct (72, 77, 78).

Three previous studies that included real-time biofeedback in their treadmill gait retraining interventions reported that changes were retained in post intervention evaluations where no biofeedback was provided. White and Lifeso (20) reported that changes were transferred to post intervention gait evaluation after an 8-week treadmill training intervention using verbal and real-time biofeedback aimed at reducing asymmetric limb loading after total hip arthroplasty (THA). Crowell and colleagues (21) reported that 3 of 5 subjects were able to significantly reduce the magnitude of their tibia's peak positive acceleration after a single 30-minute session using real-time visual feedback. In addition, Noehren and colleagues (22) reported that reduction in hip adduction and contralateral pelvic drop were retained after 8 sessions of treadmill training with biofeedback to reduce pain in runners with patellofemoral pain syndrome. Of these 3 previous studies, only Noehren and associates (22) included a longer follow-up evaluation and reported that improvements of hip mechanics persisted after 1 month. Similarly, the results of the present study showed that gained proficiency in controlling knee hyperextension patterns was evident at posttraining and 1-month follow-up (Figure 2.2). The outcomes of these studies substantiate the effects of real-time biofeedback in facilitating the acquisition and internalization of motor skills, thereby, improving learning and persistence (3, 78).

During treadmill gait retraining participants demonstrated a significant reduction in peak knee hyperextension from the first (TM1) to the last (TM6) treadmill sessions (Figure 2.3). Real-time feedback used in gait retraining, specifically, visual kinematic information, may help individuals amplify proprioceptive information (78), acquire their own strategies for modifying gait patterns, and internalize these adjustments. As shown in Figure 2.3, during the first 2 sessions, in which the greatest improvements were observed in the involved limb from beginning to end of a training session, participants might have relied more on the visual feedback to gain information about their movements. Once the strategies were acquired and internalized, participants showed carryover to the beginning of the next session and a more stable pattern, which was shown during the remaining training sessions (fourth to sixth). These speculations might corroborate the role of real-time biofeedback in improving performance, increasing awareness of knee joint position, and facilitating the learning process.

While this initial study suggests a beneficial effect of real-time biofeedback provided during treadmill gait training for correcting knee hyperextension, it is not known if these changes persist beyond the 1-month follow-up included in this study. In addition, the ability of these changes in knee kinematics to influence knee stress and any subsequent pathology is unknown. A larger study in the form of a randomized controlled trial, which would include a comparator group, blinding of the investigators, and longer follow-up assessment, is needed to further corroborate these findings.

Conclusions

The results of this study indicate that subjects were able to decrease knee hyperextension during treadmill gait retraining. The current study underscores the potential of real-time kinematic biofeedback to foster subtle changes in gait patterns that may otherwise be difficult to perceive. Gained proficiency in controlling knee hyperextension patterns during treadmill training was also evident for overground walking, in which visual cueing may be different.

Table 2.1 Peak knee extension mean values*

	Pretraining	**Posttraining**	**1-mo Follow-up**	**Pretraining to Posttraining Difference**	**Pretraining to 1-mo Posttraining Follow-up Difference**
Subject 1	7.3	-0.5	2.0	7.8	**5.2**
Subject 2	4.6	-2.1	-2.2	6.8	**6.8**
Subject 3	13.1	-3.7	5.5	16.7	**7.5**
Subject 4	9.3	1.5	7.5	7.7	**1.8**
Subject 5	12.7	0.9	13.4	11.8	**-0.7**
Subject 6	9.2	3.3	2.3	5.9	**6.9**
Subject 7	2.0	2.2	4.6	9.8	**7.3**
Subject 8	5.6	-2.0	†	7.6	**5.6**
Subject 9	9.1	-12.7	-0.6	21.8	**9.7**
Subject 10	4.1	1.2	2.7	2.9	**1.4**
Mean ± SD	**8.7 ± 3.3**	**-1.2 ± 4.6**	**3.9 ± 4.6**	**9.9 ± 5.6**	**5.2 ± 3.3**

*Individual data are based on 5 gait cycles collected during overground gait evaluations. Positive values represent knee extension.

†Subject 8 did not attend the 1-month posttraining gait evaluation.

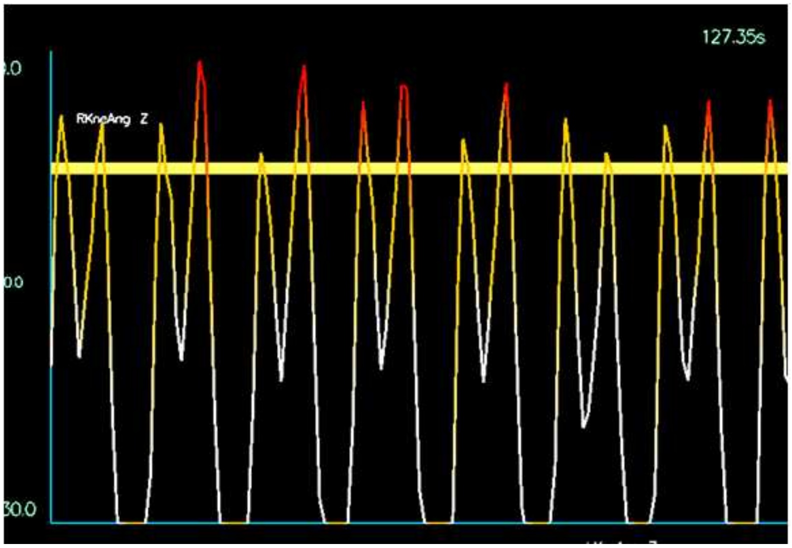

Figure 2.1 Example of real-time kinematic biofeedback provided to subjects during treadmill training. Horizontal band represent target (5° knee flexion) (Perry 1992). Vertical lines represent sagittal plane knee motion over several gait cycles.

Perry J: *Pathological Mechanisms.* In: Gait Analysis: Normal and Pathological Function pp 172, Willoughby CD, Ed.; SLACK Incorporated: Thorofare, NJ, 1992.

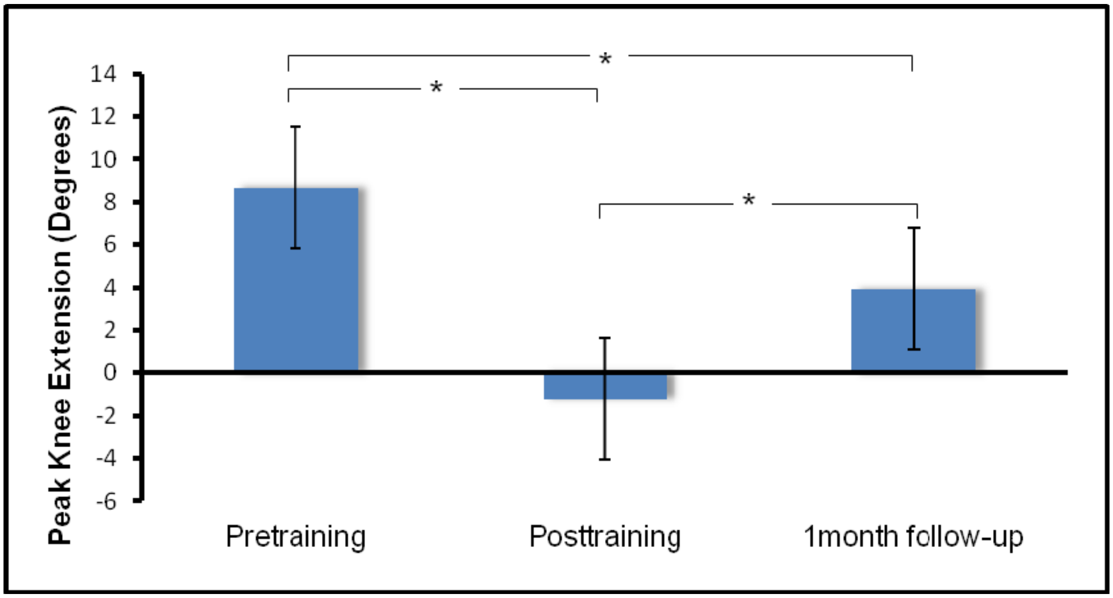

Figure 2.2 Mean peak and standard deviation of knee extension at pretraining, posttraining, and 1-month follow-up for overground gait evaluations.

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* Indicated significant differences (p<0.01)

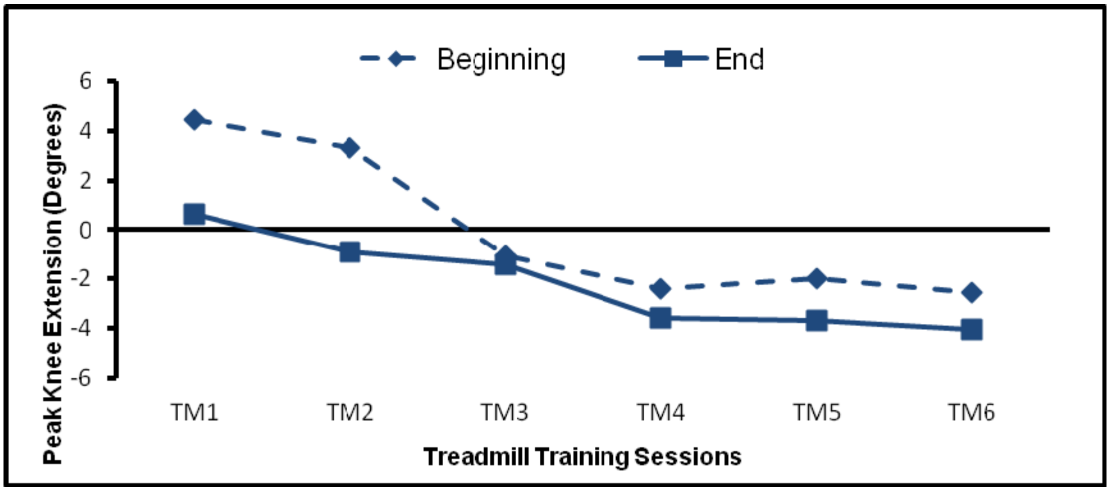


Figure 2.3 Mean (10 subjects) peak knee extension at the beginning and end of each treadmill training sessions (TM).

CHAPTER 3

EFFECTS OF FOCUS OF ATTENTION AND BIOFEEDBACK IN CONTROLLING KNEE HYPEREXTENSION IN HEALTHY WOMEN

Introduction

Clinicians are often involved in helping patients acquire or improve motor skills. Instructions typically seek to simplify a motor task by directing the patient's attention to various components of the skill. Rarely do clinicians consciously consider how their instructions influence the attentional focus of the patient. Research suggests that the patient's specific attentional orientation can have an important influence on learning motor skills (5, 6, 9). Therefore, the effectiveness of clinicians' instructions could potentially be enhanced by manipulating the instructions to induce a specific focus of attention.

Motor learning research supports the notion that when learning new skills the learner can have an internal or an external focus of attention. These two orientations of focus of attention may have different effects on motor learning (5). An internal focus of attention instruction directs the learner's attention to consciously attend to the movement (i.e. focus on their own body movements or the movement mechanics). An external focus of attention instruction directs the learner's attention to perform the task without consciously attending to the movement pattern (i.e. focus on effects of performer's movements on the environment or on a relevant external cue) (5, 6).

There is accumulating, but not universal (44-46), evidence supporting the use of an external focus of attention for the acquisition or improvement of a variety of motor skills, in both pathological (43) and non-pathological populations (5, 23, 31-35, 38-40). An external focus of attention is thought to promote the utilization of unconscious or automatic processes, whereas an internal focus of attention may result in a more conscious type of control that constrains the motor system and disrupts automatic control processes (5, 49, 50). Despite the considerable attention given to internal versus external focus of attention in motor learning studies, research assessing the implications of learner's focus of attention in rehabilitation is limited (43, 52). The effect of instructions which bias the focus of attention instructions in clinical applications needs to be investigated as it offers the possibility of enhancing the effectiveness of rehabilitation and training regimens.

The paradigm that will be used to explore the aforementioned motor learning issues is modifying knee range of motion during gait, to prevent knee hyperextension. Knee hyperextension (genu recurvatum), typically defined as more than 5° of extension, is an insidious condition mainly seen in women (65) that can have acute or long-term consequences. Knee hyperextension has been related to an increased incidence of knee injury and cartilage degeneration (60, 62, 79). Specific links to increased stress to the posterior joint capsule of the knee and the anterior cruciate ligament (ACL) (58, 64) and increased contact stress on the anterior compartment of the tibial-femoral joint (59, 63, 64) have been reported. Female athletes who hyperextend their knee are 5 times more likely to injure their ACL (62).

Previous work by our group has shown that knee sagittal plane kinematics, in women with asymptomatic knee hyperextension, could be influenced by dynamic gait training using real-time biofeedback that focused attention on the knee. Gained proficiency in controlling knee hyperextension during treadmill training was evident during overground walking immediately and 1 month after training. This study helped to validate the effectiveness of real-time kinematic biofeedback in informing individuals with knee hyperextension patterns about specific and subtle aspects of the knee movement pattern that may otherwise be difficult to perceive and appropriately modify (internal focus) (80). Given this theoretical framework, we asked the question: would training individuals to control knee hyperextension be more effective if the augmented feedback was linked to a focus of attention that was internal or external?

The purpose of this study was to examine if an external or internal focus of attention influenced the effectiveness of real-time visual biofeedback, during treadmill gait training for correcting knee hyperextension patterns, in young, asymptomatic, female subjects. We hypothesized that asking subjects to have an external focus of attention would be more effective in improving performance and retention.

Methods

Subjects

Twenty healthy women (age 26.9 +/- 5; mass 64.3 +/- 13 Kg; height 1.6 +/- 0.1 m) with no history of lower limb surgery or cardiovascular, functional or visual limitations took part in this study. Participants were screened and included in the study if they had asymptomatic knee hyperextension greater than 5° during passive range of motion. Knee hyperextension was measured in supine with the ankle resting on a 10-cm support, using standard goniometric techniques. Prior to participation, all subjects provided informed consent and the study protocol was approved by the University of Iowa's Institutional Review Board. Ten participants were randomly assigned to each, internal or external, focus of attention intervention groups (Figure 3.1).

Testing Protocol

Overground gait evaluations were conducted along an 8-m walkway, with the subjects walking at a speed of 1.3 m/s. Feedback on walking speed was provided by a member of the team who monitored walking speed relative to an overhead timing chain. The knee with the greatest amount of hyperextension, either during the passive range of motion evaluation or the initial gait evaluation, was the focus of the gait retraining intervention.

A 3-dimensional motion analysis system (Optotrak™, Northern Digital Inc., Waterloo, Ontario - Canada) was used to collect kinematic data during gait. Three non-collinear infrared markers were used to track each of the 7 segments: 2 feet, 2 legs, 2 thighs, and pelvis. Marker coordinate data were collected at 60 Hz and filtered at 6 Hz.

To define the axes of each of the 7 segments, an anatomical model was created by digitizing standard bony landmarks: anterior and posterior superior iliac spines, greater trochanters, lateral and medial epicondyles, lateral and medial malleoli, posterior heel, second toe, and the head of the fifth metatarsal. Kinematic data were calculated using Visual 3D (C-Motion, Germantown, MD). This modeling approach was used for the 4 overground data collections at pretraining, posttraining (a minimum of 2 days and maximum of 5 days following the sixth training session), 1-month, and 8 month follow-up in which 5 walking trials were collected (4 full gait cycles were analyzed for each walking trial). A description of the data collection flow is presented in Figure 3.2.

Training Protocol

Following the initial evaluation, subjects participated in supervised treadmill training twice a week for three weeks. Each training visit lasted one hour and consisted of three 8-minute treadmill training sessions, with 3-minute rest periods. During each 8-minute treadmill training sessions, participants received verbal and real-time visual biofeedback from the second to the sixth minute (Figure 3.3). The same modeling approach used for the four over-ground data collections was used for treadmill gait training, in which subjects in both intervention groups were provided with knee kinematic data in real-time (Visual 3D). Knee sagittal plane kinematics data for 3 previous gait cycles were provided on a computer screen that was placed on a table (150 cm in height) about 1 m in front of the subjects. The real-time biofeedback screen consisted of a horizontal yellow band that represented the target area where subjects attempted to center the motion and vertical lines that represent the movement of the knee in the sagittal plane, Figure 3.4. The target horizontal yellow band was set at 5º of knee flexion. Vertical lines above the horizontal yellow band represented less than 5º of knee flexion.

Intervention Groups

While both intervention groups visualized the sagittal plane knee angle (Figure 3.4), the instructions provided to each group induced a different interpretation of the biofeedback presented. Participants in the internal focus of attention group were instructed to associate the display line with the movement of the sagittal plane knee angle under investigation. During the first treadmill training session, but before the training began, participants in the internal focus of attention group practiced observing how changes in their knee angle affected representations on the monitor. During training these participants were instructed to "bend your knee, keep your joint angle within the desirable angle, and try to maintain a normal gait pattern", (Figure 3.4). For participants in the external focus of attention group, the feedback was not overtly linked to the knee motion. Participants in this group were provided visual feedback while walking and instructed to "try to bring the peak vertical lines as close as possible to the target horizontal yellow line" (Figure 3.4). Foci of attention instructions (internal or external) were reinforced at the beginning of each 8-minute treadmill training session to remind participants where they should focus their attention.

Debriefing Process

After the 6 training sessions, participants were debriefed using a standardized open ended set of questions. The objective of the debriefing process was to discover where participants oriented their attention during the training to determine compliance with training instructions.

Dependent Variables and Data Analysis

Groups were tested for differences in age, height, weight, and passive range of motion using a t-test. Sagittal plane, maximum knee extension values during overground walking (over 5 walking trials at 1.3 m/s), were averaged and collected at pretraining, posttraining, 1-month, and 8 month follow-up. Comparisons of average peak knee extension values at pre-training, post-training, 1-month, and 8-month follow-ups were made using a 2-way (time and attention group) repeated-measures analysis of variance (ANOVA). Significant results were explored using the Tukey Studentized range follow-up test ($p < 0.05$). All statistical testing was performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA). Missing data were calculated using an imputation technique that minimizes the effect on the error mean square and interaction effect (74).

A prospective power analysis was performed using the data collected in a descriptive cohort study designed to evaluate the effect of sex on genu recurvatum and to report representative values of these measures from a sample of 118 healthy active adults.1 This study reported a difference of 5.7 +/- 3.2 degrees of genu recurvatum in women versus men participating in this study. We anticipated a change in the knee angle of at least 3 degrees with a standard deviation of 3.2 degrees (65). In order to obtain 90% power, we required a sample size of 10 subjects per group.

Results

Participants' age, height, weight, and passive range of motion of the knee under investigation were similar ($p>0.05$) in both intervention groups. Mean (+/- SD) knee passive range of motion was 10º +/- 2.9º (range, 6° - 14°) and 8º +/- 1.4º (range, 6° - 10°) in the internal and external focus of attention groups, respectively. Pretraining gait evaluations showed that 11 subjects had greater knee extension in their right knee. Maximum knee extension occurred at initial contact in 13 subjects and at toe-off in 7 subjects. Mean knee extension during pretraining gait evaluations was 6.7° +/- 3.3° and 6.4° +/- 3° in the internal and external focus of attention groups, respectively. Individual knee extension range of motion at passive range of motion (PROM) and during pretraining (Pre), posttraining (Post), 1-month (1M), and 8-month (8M) overground gait evaluations are presented in Table 3.1. Mean knee extension range of motion during posttraining, 1-month, and 8-month follow ups are shown in Figure 3.4.

All 20 subjects underwent pretraining and posttraining gait evaluations. One participant in the internal focus group missed the 1-month follow up gait evaluation

(Figure 3.1). Four participants (3 in the internal focus group and 1 in the external focus group) missed the 8-month follow up gait evaluation. There was a significant reduction (P<.0001) in knee extension range of motion between pretraining, posttraining, and 1-month follow up overground gait evaluations (Figure 3.5). There was no interaction of time and focus of attention group (P=0.39) and there was no effect of focus of attention groups (P=0.45).

The debriefing process indicated that five participants in the internal focus of attention group oriented their attention to their knee joint during training sessions 1 to 3 and to other body parts during the remaining sessions. Five participants in the internal focus group switched their attention to either other body parts (e.g. feet, thighs) or to an external focus of attention (e.g. step length) through all 6 training sessions. Participants in the external focus of attention group focused on the target line during the first two or three training sessions, but with some exceptions. Four participants in this intervention group reported that their attention was focused on a body part (e.g. gluteus muscles, abdominal muscles, and foot) at least once during the training sessions. Two subjects in the external focus group indicated that they were attempting to determine what the lines represented. One participant in this intervention group reported that she focused on her overall posture when walking.

Discussion

The purpose of this study was to examine if an external or internal focus of attention influenced the effectiveness of real-time visual biofeedback during treadmill gait training for correcting knee hyperextension patterns in young, asymptomatic, female subjects. We hypothesized that asking subjects to have an external focus of attention would be more effective in improving performance and retention. The results of the present study showed significant reductions in knee hyperextension patterns immediately following training and at 1 and 8-month follow-ups. There were not significant differences between intervention groups.

The magnitude of knee hyperextension that we observed (mean +/- SD passive range of motion, 8.8º +/- 2.4º; and knee extension during overground gait, 6.6° +/- 3.1°) is similar to previous reports for this population (7.3°+/- 4.4°) (68). Compared to another study where knee hyperextension tended to be overcorrected (68), the results of the present study show that after the 6 sessions of treadmill gait retraining the knee maintained a more normal extension angle (+/- 5°) when walking over ground. In addition, increased proficiency in controlling knee hyperextension patterns was evident at 1-month and 8-month follow-ups. The outcome of the present study helps validate the effectiveness of real-time kinematic biofeedback in informing individuals about specific and subtle aspects of the movement pattern that would otherwise be difficult to perceive and appropriately correct (3, 72).

The methodology used in the current study was similar to the methodology used by Shea & Wulf (31) and Maxwell & Masters (44). Our inability to find different outcomes based on focus of attention is similar to Maxwell & Masters (44) who also found no differential effects of attentional focus during learning and retention (Figure 3.5). Shea & Wulf (31), on the other hand, found a clear advantage of an external focus of attention. The inconsistency of results with Shea & Wulf (31) might be due to the different levels of compliance with focus of attention instructions, which might be related to the number of training sessions used in both studies. As the number of training sessions increased some participants may have switched their attention despite the instructions provided at the beginning of each training sub session. Wulf et al (4) reported that when given the opportunity to focus independently, performers preferred to attend externally, as it resulted in more effective performance. The speculation that some participants in the current study did not rely on a single focus of attention seems to be supported by the results of the debriefing session which showed that, after training sessions 3 or 4, some participants in both intervention groups used a different focus than intended by the investigator. In contrast, by providing only 2 training sessions, during 2 consecutive days, Shea & Wulf (31) might have been able to sustain the instructed attentional focus. An additional difference with Shea & Wulf was that in contrast to their study, the external focus group in the current study was not cued to relate the augmented feedback to a particular performance variable, which may have affected the ability of these subjects to take full advantage of the feedback.

Consistent with the intuitive shift by a number of individuals to an external focus of attention, is work that suggested that highly skill performers perform better with external attention instructions than with internal focus instructions (46, 81). In the current study, participants' automated walking pattern qualified them as well-learned performers and studies have suggested that compared to novice performers, well-learned performers appear to require different levels of attentional resources for successful learning (81).

While our data did not establish differences in retention between the two groups, there were trends in the data that point to possible differences. The results of the current study showed that at 1-month and 8-month follow ups (Figure 3.5) participants in the external focus of attention showed a trend for better long-term retention of performance gains compared to the internal focus of attention groups. Previous work has identified improved retention as a potential benefit of having an external focus of attention (6). The lack of instructional compliance by the participants in the present study, however, may have contaminated the results and thereby prevented us from drawing absolute conclusions regarding the focus of attention. Thus, further research should address this effect as previous attempts to correct knee joint sagittal alignment have had limited long term success (64, 67, 68).

Conclusions

The results of this study support the effects of real-time biofeedback in facilitating the acquisition and retention of proficiency in controlling knee hyperextension gait patterns, documenting that the retention is sustained for up to 8 months. However, there were not significant differences when augmented feedback was linked to groups that had a different focus of attention. It is not known if participants actively switched to an external focus of attention despite the instructions provided during training. Tests to ensure instructional compliance should be used in future studies. In addition, while the results demonstrate that knee hyperextension may be reduced over time, we do not know how the training affected participants' gait pattern outside the laboratory.

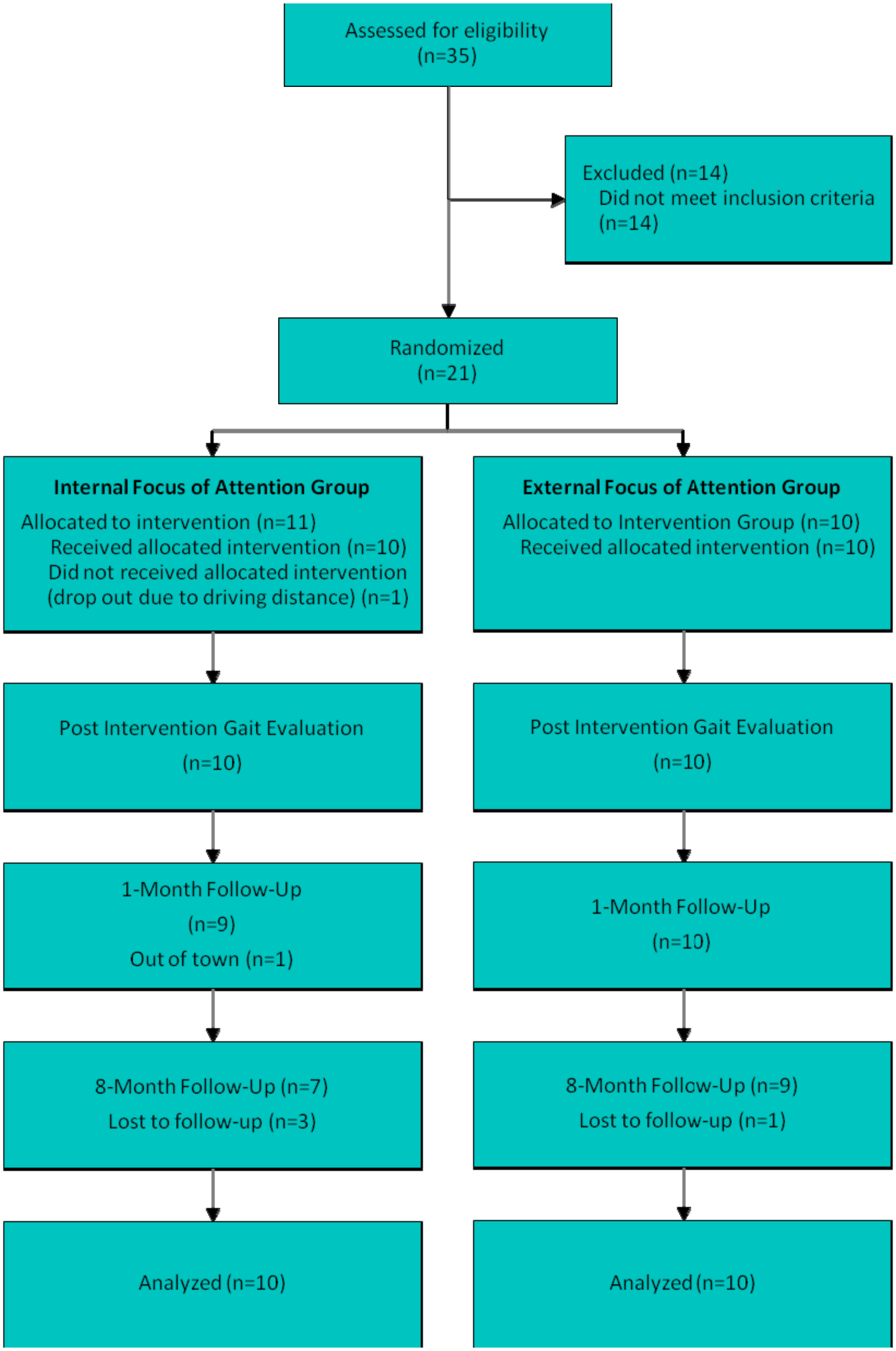


Figure 3.1 Flow diagram for participants' involvement.

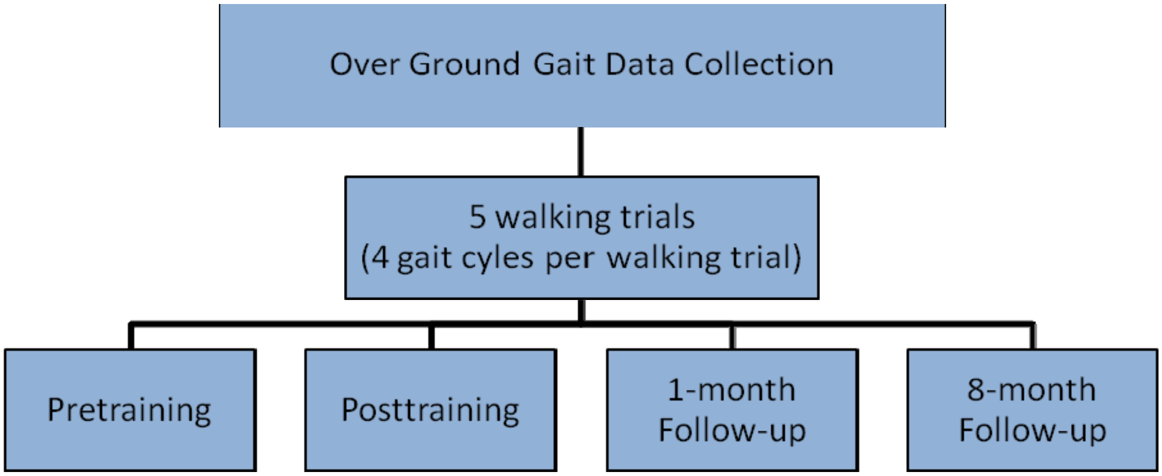


Figure 3.2 Flow of data collection.

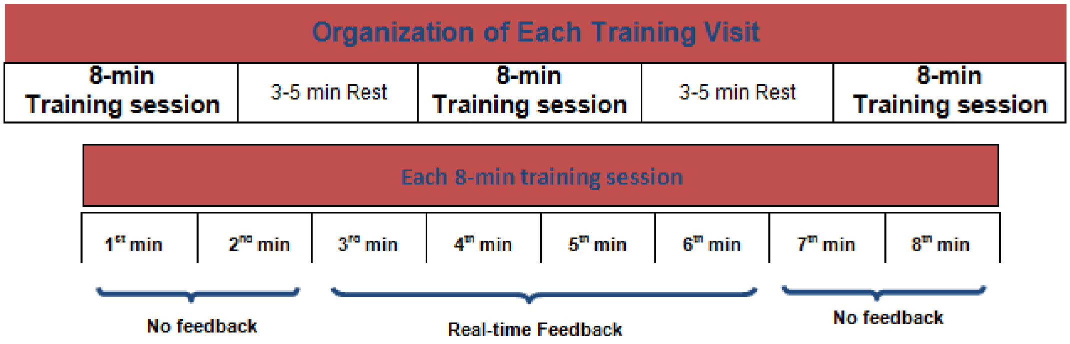
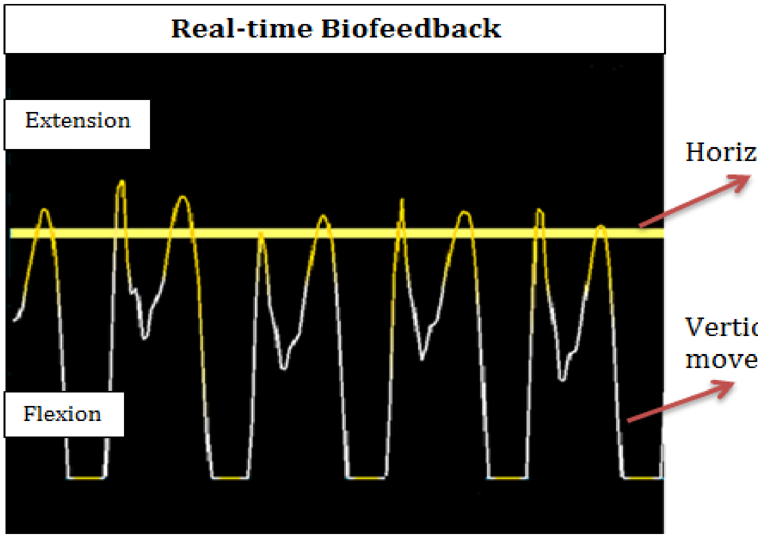


Figure 3.3 Organization of treadmill training sessions. Real-time biofeedback (knee sagittal plane kinematics) was provided during 4 minutes of each 8-minute treadmill training session.



Horizontal band: target (5° flexion)

Vertical lines: knee sagittal plane movement.

Figure 3.4 Real-time biofeedback: Horizontal band represents the target area where subjects attempted to center motion (5° flexion). Vertical lines represent the movement of the knee in the sagittal plane. Vertical lines above the horizontal yellow band represented less than 5º of knee flexion.

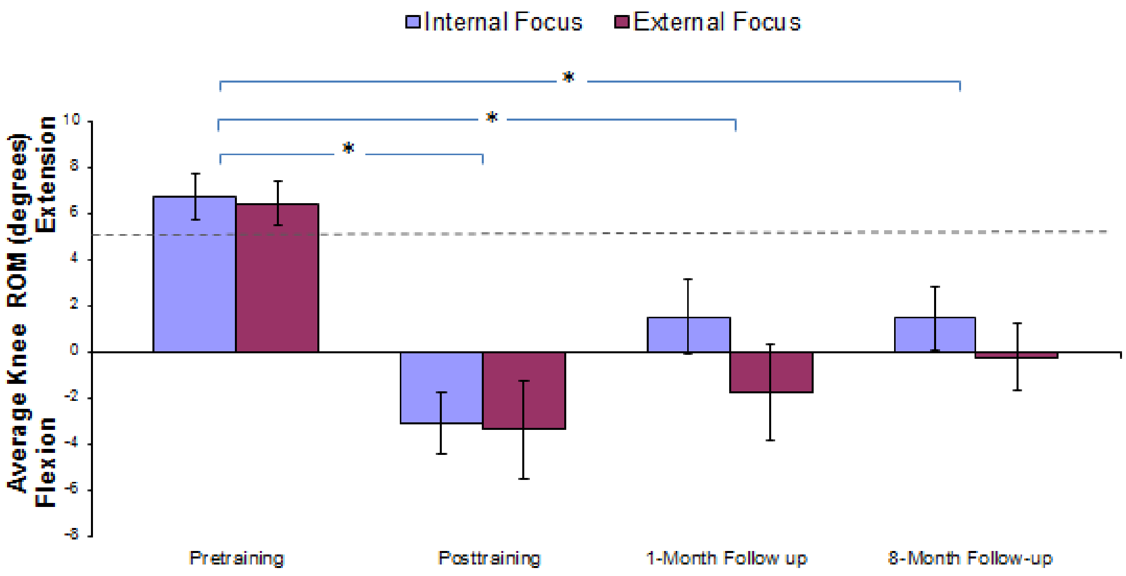


Figure 3.5 Mean and standard error knee extension range of motion across participants over time. Values above horizontal dotted line mean hyperextension. There was a significant reduction (P<.0001) in knee extension range of motion between pretraining, posttraining, and 1-month follow up overground gait evaluations. Significant differences are represented by an asterisk (*).

Table 3.1 Individual knee extension range of motion during overground gait evaluations*

INTERNAL FOCUS OF ATTENTION GROUP						EXTERNAL FOCUS OF ATTENTION GROUP					
	PROM	**Pre**	**Post**	**1M**	**8M**		**PROM**	**Pre**	**Post**	**1M**	**8M**
Subj1	6	5.4	-3.0	-1.5	1.5	Subj1	8	8.3	2.8	8.5	7.2
Subj2	10	1.5	-5.4	-5.0	-3.6	Subj2	7	6.3	-6.8	-5.0	-2.5
Subj3	14	11.2	-5.8	3.8	3.1	Subj3	8	8.9	-2.3	-2.7	0.5
Subj4	11	5.6	-1.5	4.2	3.0	Subj4	10	11.3	8.9	8.7	6.2
Subj5	6	11.6	-1.6	12.9	9.5	Subj5	10	5.7	-5.1	1.4	3.0
Subj6	13	8.9	2.3	1.2	5.2	Subj6	8	5.1	-16.8	-8.4	-5.2
Subj7	12	8.5	-0.6	2.7	3.4	Subj7	6	5.0	-5.3	-7.4	-6.3
Subj8	12	4.8	-2.9	-1.0	-4.1	Subj8	9	4.7	-6.6	-4.8	-3.6
Subj9	9	6.6	-13.0	-4.2	-1.7	Subj9	6	0.3	-1.5	1.3	0.9
Subj10	7	3.3	-0.1	1.9	-1.9	Subj10	8	8.6	-1.3	-9.3	-2.9
Mean	**10.0**	**6.7**	**-3.2**	**1.5**	**1.5**	**Mean**	**8.0**	**6.4**	**-3.4**	**-1.8**	**-0.3**
SD	**2.9**	**3.3**	**4.2**	**5.0**	**4.3**	**SD**	**1.4**	**3.0**	**6.7**	**6.5**	**4.6**

*Positive values mean knee extension range of motion.

CHAPTER 4

LEARNING EFFECTS OF A TRAINING PROGRAM USING LEARNER'S FOCUS OF ATTENTION INSTRUCTIONS TO CORRECT KNEE HYPEREXTENSION GAIT PATTERNS IN YOUNG WOMEN

Introduction

Motor learning interventions to teach or modify motor patterns often find that the improvements observed during the training phase do not transfer to other environments or activities (1). One of the most important objectives of an effective motor learning intervention is to ensure that once the skill is learned it is retained (retention) and can effectively be used in new situations the learner may encounter (transfer). Studies have proposed that transfer of learning could be achieved by assisting the learner in finding individual optimal performance patterns that would allow controlling variations of the learned movement pattern in a more automatic way (1). Finding strategies to influence transfer of motor skills is the subject of research (1, 82, 83).

Motor learning research has suggested that learning of motor skills seems to be enhanced if the learner adopts an external focus of attention (e.g. directing attention to the effect of an action on the environment or environmental cue outside of the body) rather than the more traditionally used internal focus (e.g. directing attention to bodily movements involved in the execution of the motor skill). The advantageous nature of an external focus of attention is thought to arise as a consequence of the utilization of more natural control mechanisms that allow automatic processes to regulate movements (5, 6, 35). This idea led to the formation of the constrained action hypothesis, which states that "conscious attempts to control movements interfere with automatic motor control processes, whereas focusing on the movement effects allows the motor system to self-organize more naturally, unconstrained by conscious control" (5). Despite the considerable attention given to internal versus external focus of attention in motor learning studies, research assessing its retention and transfer effects (32, 34, 84) is limited and has not been investigated in clinical applications.

The implications of learner's focus of attention instructions in clinical applications needs to be investigated as this learning strategy offers the possibility of enhancing the lasting effects of rehabilitation and training regimens. Some of the motor learning activities that clinicians typically work on (related to developing the patient's range of motion, flexibility, muscle force or endurance) often involve instructing patients to focus on the body segment under treatment. However, it is unknown whether encouraging conscious control of movement promotes effective motor learning.

The purpose of this study was to investigate the efficacy of a treadmill gait retraining programs, using different learner's focus of attention instructions, for correcting knee hyperextension in asymptomatic females. The specific aims of this study were to examine the effectiveness of internal and external focus of attention by: 1) assessing learning acquisition over six training sessions, 2) establishing short-term (2-5 days after training) and long-term (4 months after training) retention; and 3) assessing transfer effects of a treadmill retraining program to overground walking and obstacle crossing. It was hypothesized that women in the external focus of attention group will demonstrate a greater speed of acquisition, greater short and long-term retention, and a greater percentage of transfer to untrained tasks than women in the internal focus of attention group.

Methods

Subjects

Twenty one healthy women (age 22 +/- 4; mass 64.2 +/- 9.3 Kg; height 1.7 +/- 0.1 m) with no history of lower limb surgery or cardiovascular, functional or visual limitations, no hypermobility syndrome, and no history of previous participation in a knee injury prevention program took part in this study. Participants were screened and included in the study if they had asymptomatic knee hyperextension greater than 5.5°

during passive range of motion and during overground walking. The knee with the greatest amount of hyperextension during overground walking evaluation was identified to be the focus of the gait retraining. Prior to participation, all subjects provided informed consent and the study protocol was approved by the University of Iowa's Institutional Review Board. Participants were randomly assigned to either internal or external focus of attention intervention groups. Figure 4.1 shows a flow diagram of the intervention.

Testing Protocol

Participants underwent a physical evaluation to assess: knee passive range of motion (using conventional goniometric techniques); lower limb isometric muscular strength (using manual muscle techniques); joint mobility index (using Beighton Joint Mobility Index BJMI); and knee range of motion during overground walking, obstacle crossing, and level treadmill walking. Previous work on knee joint kinematics during functional activities in women with knee hyperextension showed that young females with knee hyperextension tend to hyperextend during overground and treadmill walking and during obstacle crossing, when the limb is the trailing limb (Appendix chapter, Figure A.2).

Knee kinematics were collected during walking tasks using a three-dimensional motion analysis system (Optotrak™, Northern Digital Inc. Waterloo, Ontario - Canada) (80). Three non-collinear infrared markers were used to track each of the following body segments: feet, legs, thighs, pelvis, and trunk. Marker coordinate data was collected at 60 Hz and filtered at 6 Hz. An anatomical model was created by digitizing standard bony landmarks to define the axes of each of the eight body segments. To measure differences in knee kinematics, the greater trochanter was used to define the proximal femur. Kinematic data was processed using Visual 3D software (C-Motion). The same modeling approach was used for all testing and training sessions.

Overground walking

Participants were asked to walk several times along an 8-meter walkway. To reduce variability among subjects, walking speed was individually adjusted using each participant's leg length, based on a nominal speed of 3 mph (85). Set walking speed was monitored by the evaluator, using an overhead timing chain, and verbal cues were provided to the subjects. Kinematic data on 20 walking trials were collected. The same protocol was used at post-training and 4-month follow-up evaluations.

Obstacle crossing

Subjects were asked to walk at a self-selected pace along an 8-m walkway and crossed a height-adjustable obstacle composed of a 1.5m long aluminum tube with a diameter of 1.5 cm placed across a metal frame. The tube was light and rigid so it would have dropped off the frame when contacted. Test conditions included crossing the obstacle at a height equivalent to 10% of leg length. Twenty trials were collected with the limb under investigation as the trailing limb. The initial self-selected walking speed was the target walking speed during the posttraining and 4-month follow-up evaluations.

Treadmill walking

Although participants had experience with treadmill walking, participants were given 5 minutes to familiarize themselves with the study's treadmill and their walking at their individually adjusted walking speed. Kinematic data (20 seconds) were collected after the first 5 minutes of treadmill walking. The same protocol was used at post-training and 4-month follow-up evaluations.

Training Protocol

After the initial evaluation, participants were randomly assigned to external or internal focus of attention instruction groups. Figure 4.2 shows an overview of the training intervention. Subjects participated in a personalized six-visit (one hour each) treadmill gait retraining program (twice a week) for correction knee hyperextension on the knee under investigation (knee with the greatest amount of extension during overground walking). Each of the six training visits consisted of three 8-minute sessions, with 3-minute rest periods between sessions. Twenty seconds of kinematic gait data were collected at the beginning and end of each treadmill training session to compare control of knee sagittal alignment during training as a function of focus of attention instructions. During each 8-minute session, the protocol presented in Figure 4-3 was used.

Placement of infrared marker set

Bright color extensions/wands (off-set by 5 cm) were attached to orthoplast sticks that held the infrared marker triads on the legs and thighs (Figure 4.4). Participants in both intervention groups used the same marker set. The extensions/wands were the focus of attention for participants in the external focus group. The bright color was intended to help participants get a stronger mental image of the orientation of the wands and keep the focus of attention during training. By off-setting the wands away from the body it might be easier for subjects to visualize the wands during the orientation period. (33).

Orientation to training

Before each training session began, a 5-minute orientation period was provided to participants. During the orientation period participants were asked to identify changes in knee or wand angle, as represented in pictures of either knee angle or position of the wands in the limb of interest. Figure 4.5 shows an example of the images that were presented to participants. Participants were also familiarized with language used to provide knowledge of results and training instructions.

Identification of changes in knee or wand angle

Participants in both intervention groups spent between 2-3 minutes identifying changes in either the knee angle (internal focus group) and or wand angle (external focus group) during weight-bearing position and treadmill walking (self-selected pace).

Familiarization with knowledge of results cues provided during training

Knowledge of results on the knee (internal focus) or wands (external focus) movement was provided at the 2nd, 4th, and 6th minute of each 8-minute session (Figure

4.6). During the orientation period, participants were informed that “the feedback that you will receive during training will refer to the result of multiple gait cycles.” The feedback was provided using 3 specific cues: “too little” (<0° extension), “good” (0-5° flexion), “too much” (>5° flexion).”

Focus of attention instructions

Participants in both intervention groups received instructions to orient their attention to either their knee angle (internal focus of attention) or the angle formed by two wands attached to their thighs and legs (external focus of attention). Participants in the internal focus of attention group were instructed to “concentrate on the motion of your knee, control the knee angle within the desirable position, and try to maintain a normal gait pattern.” Participants in the external focus of attention group were instructed to “concentrate on the motion of the wands, control the wand’s angle within the desirable position, and try to maintain a normal gait pattern.”

Reinforcement of instructional compliance

During training and while engaged in controlling their knee angle (internal focus) or wand angle (external focus group), participants were asked to judge the situation of their knee or wands. Participants were asked to respond “too little”, “good”, or “too much” if knee or wands are in <0° extension, 0-5° flexion, or >5° flexion, respectively. The trainer judged the accuracy of participant’s responses using real-time knee kinematic displays, representing the previous three gait cycles. Accuracy of responses was logged to determine compliance with instructions.

Training

At the beginning of each 8-minute session, participants were reminded of their attentional focus, knowledge of results, and were asked to “try to keep a mental image of the movement of your knee (internal focus)/wands (external focus) and try not to think about anything else during the training session.”

Debriefing

At the end of the first five treadmill training sessions, participants were asked to answer 5 questions about their thoughts during each training session using a Likert-type format (Figure 4.7). At the end of the last treadmill training sessions, participants were debriefed using a standardized open-ended set of questions (Figure 4.8). The objective of the Likert-type and standardized open-ended questionnaires was to discover where participants oriented their attention during the training; to determine compliance with training instructions.

Data Analysis

Descriptive statistics (age, height, weight, joint mobility index, lower limb isometric strength and passive range of motion) were calculated using Excel. Peak sagittal plane knee extension, for twenty gait cycles, during over ground walking, obstacle crossing, and treadmill walking were calculated, using Visual 3D, and analyzed at pretraining, posttraining, and 4-month follow-up. In addition, peak sagittal plane knee extension for twenty gait cycles, collected at the beginning and end of each treadmill training session, were calculated using Visual 3D.

Peak knee extension values, for twenty gait cycles, collected over time, were used to calculate the overall error (root mean square error, RMSE). The overall error (RMSE) was used to compare how successful each subject was in achieving the target (set at 5° of knee flexion for the purpose of this study) during gait activities (over ground walking, obstacle crossing, and treadmill walking) and at the beginning and end of each treadmill training session. Figure 4.9 shows a diagram of how data collected over time were analyzed.

Learning Acquisition

To assess learning acquisition as a function of learner’s focus of attention**,** the overall error (RMSE) at the beginning and end of each of the six treadmill training sessions were compared between intervention groups.

Retention

To assess short-term (2-5 days after training) and long-term (4 months after training) retention, the overall error (RMSE) at the end of the last treadmill training sessions and posttraining or 4-month follow-up were compared between intervention groups.

Transfer

To assess transfer effects of treadmill retraining program to overground walking, the overall error (RMSE) during overground walking at posttraining was compared between intervention groups. To assess transfer effects of treadmill retraining program to obstacle crossing, the overall error (RMSE) during obstacle crossing at posttraining was compared between intervention groups.

Statistical Analysis

Categorical data were summarized with frequencies and percentages. Continuous data were examined with scatter plots and tests for normality. Linear mixed models for repeated measures (to account for variability and correlation of measures over time) were used to assess for significant differences in **learning acquisition** and short and long-term **retention** between intervention groups. Group comparisons of **transfer** to untrained activities were made using the Mann-Whitney U-test (Wilcoxon two-sample test). The Likert-type debriefing questionnaire was analyzed using measures of central tendency and frequency tables. Significant results were explored using Tukey's Studentized Range follow-up test ($\alpha < 0.05$). All statistical testing were performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA). Level of significance was set at $p = .05$ for all analyses. Missing data were calculated using an imputation technique, which minimizes the effect on the error mean square (74).

Results

Participants' age, height, weight, and passive range of motion of the knee under investigation were similar ($p>0.05$) in both intervention groups. Mean (+/- SD) knee passive range of motion was 8.2º +/- 1.8º (range, 6° - 11°) and 7.6º +/- 1.3º (range, 6° - 9°) in the internal and external focus of attention groups, respectively. Pretraining gait evaluations showed that 13 subjects had greater knee extension in their right knee. Maximum knee extension occurred at initial contact in 13 subjects and at toe-off in 8 subjects. Mean peak knee extension during pretraining treadmill walking was 12.2° +/- 4.8° (range, 3.3° - 20.4°) and 10.6° +/- 4.3° (range, 3° - 17.4°) in the internal and external focus of attention groups, respectively. Mean peak knee extension during pretraining overground walking was 13.4° +/- 3.7° (range, 5.5° - 21.9°) and 14° +/- 3.2° (range, 9.4° - 20°) in the internal and external focus of attention groups, respectively. Mean peak knee extension during pretraining obstacle crossing (knee of interest as trailing limb) was 12.1° +/- 5.4° (range, 4° - 24°) and 10.7° +/- 5.4° (range, 1.7 ° - 19°) in the internal and external focus of attention groups, respectively. All 21 subjects attended six treadmill training sessions and underwent pretraining and posttraining gait evaluations. Three participants (two in the internal focus group and one in the external focus group) missed the 4-month follow up evaluation.

The debriefing process indicated that approximately 90.9% of participants in the internal focus of attention group agreed (52.7% and 38.2%, strongly agreed or agreed, respectively) that feelings from their knees were present in their thoughts during the six training session. In addition, approximately 86% of participants in the external focus of attention group agreed (40% and 46%, strongly agreed or agree, respectively) that the wands on their legs were present in their thoughts during the six training sessions. Results of the debriefing process are presented in Table 4.1.

Learning Acquisition

The results for learning acquisition, as determined by the overall error (RMSE) measure at the beginning and end of each training session, showed that there was not a significant interaction of focus of attention group and time (p=.44). There was not a significant group effect (p=.53). There was a significant time effect (p<.0001).

Significant findings are shown in Figure 4.11. Individual and mean overall error values in both intervention groups are shown in Figure 4.10 and 4.11, respectively. There was a significant reduction (p<.0001) in knee extension range of motion between treadmill walking at pretraining and posttraining.

Retention

The results for retention, as determined by the overall error (RMSE) measure at the end of the last treadmill training sessions and posttraining (short-term retention) or 4-month follow-up (long-term retention), showed that there was not a significant interaction of focus of attention group and time (p=.43). There was not a significant group effect (p=.26). There was a significant time effect (p=.033). There was not a significant difference between intervention groups during treadmill walking at the last training session (p= .48), posttraining (p=.88), and 4-month follow-up (p= .11). Overall errors (RMSE) during treadmill walking overtime, in both intervention groups, are presented in Figure 4.12.

Transfer

The results for transfer to overground walking, as determined by the overall error (RMSE) measure during overground walking at posttraining, showed that there was not a significant difference in transfer to overground walking (p= .36) between intervention groups. Participants in the internal focus of attention group showed a median of 5.7 (IQR= 3.5 - 7.9) overall error during overground walking at posttraining. Participants in the external focus of attention group showed a median of 7.9 (IQR= 5 – 10.9) overall error during overground walking at posttraining.

The results for transfer to obstacle crossing, as determined by the overall error (RMSE) measure during obstacle crossing, showed that there was no significant difference in percentage of transfer to obstacle crossing (P=.13) between intervention groups. Participants in the internal focus of attention group showed a median of 6.9 (IQR= 5.2 – 8.5) overall error during obstacle crossing at posttraining. Participants in the external focus of attention group showed a median of 8.7 (IQR= 6.4 – 11) overall error during obstacle crossing at posttraining. Average transfer to overground and obstacle crossing across participants in the internal and external focus of attention groups are shown in Figure 4.13.

Discussion

The purpose of this study was to investigate the efficacy of a treadmill gait retraining program using learner's focus of attention instructions in correcting knee hyperextension in asymptomatic females. The specific aims of this study were 1) to assess learning acquisition, 2) to establish short-term (2-5 days after training) and long-term (4 months after training) retention; and 3) to assess transfer effects of a treadmill retraining program to overground walking and obstacle crossing. It was hypothesized that women in the external focus of attention group would demonstrate a greater acquisition of learning, greater short and long-term retention, and a greater percentage of transfer to untrained tasks, than women in the internal focus of attention group. The results of the present study indicate that there were not differences in learning acquisition, short and long-term retention, and transfer to overground walking and obstacle crossing between intervention groups. Over time changes in overall error (RMSE) and knee extension ROM are shown in Figures 4.14 and 4.15, respectively.

The magnitude of knee hyperextension that we observed at passive range of motion (mean +/- SD passive range of motion, 7.9º +/- 1.6º) is similar to previous reports for this population (7.3°+/- 4.4°)(68); (9.6º +/- 3.0º)(80); (8.8º +/- 2.4º) (Chapter 3, Table 3.1). The magnitude of peak knee hyperextension measured during overground walking (14.2 º +/- 4º) was higher than previously reported (8.7° +/- 3.3°) (80); (6.6° +/- 3.1°) (Chapter 3, Table 3.1). The difference in magnitude of peak knee extension during overground walking might be because PROM was used as the criteria for inclusion of participants in previous studies. In the present study, the main inclusion criterion was knee range of motion during overground walking. As previous work showed that PROM is not a good predictor of knee range of motion during gait activities (see Appendix, Table A.3), the inclusion criteria might have biased the magnitude of hyperextension in previous studies to lower values during gait. In contrast to some previous work, where knee hyperextension was noted at toe-off (Noyes et al. 1996), the majority of subjects (13 of 21) in the current study had the greatest hyperextension at initial contact. The phase in the gait cycle (initial contact) where knee hyperextension was found to be the greatest is similar to previous studies done by our group (7 of 10 subjects) (80); (13 of 20 subjects) (Chapter 3).

Previous studies assessing learner's focus of attention have used tasks involving upper extremities (39, 41, 45, 46, 49, 50, 84, 86-89), balance (4, 23, 31-38, 42-44, 90), assisted bench-press performance (91), jumping (51, 92) and lofted passes to reach a specific target (42, 93), and a gymnastic routine (94). Contrary to previous tested activities, gait is an automated repetitive motor pattern that does not require constant conscious control (95). The generation of gait has been attributed mainly to spinal and subcortical regions of the central nervous system (95) and little or intermittent involvement of the motor cortex (96). A previous study by our group assessed the effectiveness of augmented feedback linked to an internal or external focus of attention during a treadmill gait retraining program (Chapter 3). Contrary to our previous gait training study, augmented feedback was not used in the present study to encourage conformity with the focus of attention instructions as augmented feedback could lead participants to adopt and external focus regardless of the instructions provided during training.

Studies assessing learner's focus of attention have reported that participants did not always rely on a single focus of attention and used a different focus than intended by the investigator (36, 44). To improve instructional compliance, previous studies have used brief reminders on focus of attention before each trial (36), asked participants to estimate their perceived performance after each trial (46), shown graphic symbols of the key focus of attention words (89), or asked participants to report the situation of the limb under study upon hearing a random tone (93) to complement focus of attention instructions. In addition, instructional compliance was tested using verbal protocols or questionnaires as part of the debriefing process (44, 45, 89). In the present study, during training and while engaged in controlling their knee angle (internal focus) or wand angle (external focus group), participants were asked to judge the situation of their knees or wands at a specific point in time. In addition, pictures of either knee or wands in the involved side were shown to participants during training to maintain a mental image of their instructed focus of attention. The strategies used in the present study to reinforce participant's instructional compliance seem to be supported by the results of the debriefing process which indicated that the majority of participants in both, internal and external, intervention groups maintained the instructed focus of attention during the training sessions

Related to **acquisition,** there was a significant reduction in the overall error (RMSE) (Figure 4.14) and knee extension range of motion after the treadmill training sessions (Figure 4.15). However, there was no significant difference between intervention groups. Previous studies on learner's focus of attention have shown inconclusive results. Most studies have shown that external focus of attention instructions improves learning acquisition in dynamic balance tasks (31, 33, 36, 38, 90), upper extremity tasks (39, 46, 49, 50), jumping (51, 92), lofted passes (42), and bench-press performance (91). A group of studies, involving novice learners, however, have reported better performance with internal focus of attention instructions (46, 94). Other studies have reported no significant differences between intervention groups in balance tasks (34, 35, 37, 43), upper extremity tasks (41, 41, 44, 45, 84, 87, 88). While the results of the present study are consistent with the latter studies; there are differences in the training intervention design between the previous and present studies. Contrary to the present study, in which participants received six training sessions, previous studies have only included two or three training sessions. The number of training sessions could have allowed participants in the present study to practice and acquire more consolidated learning. As shown in Figure 4.11, the greatest effect of training was observed within the first two training sessions; however, participants in both intervention groups showed modifications in the overall error (RMSE) during the third and fourth training sessions. The overall modifications observed during training seem to plateau after the fourth training session. The learning curve observed during training in the present study seems to follow the learning curve observed in studies assessing learning paradigms in animal models (97) where most of the improvement was observed within the first session with reduction of intersession retention in later sessions.

Even though participants in both intervention groups showed a reduction in overall error after treadmill training, improvements observed within and between training sessions seem to indicate that participants in the internal focus of attention group showed a better acquisition of learning than participants in the external focus of attention group. Besides the significant acquisition of learning observed during the fourth training sessions, participants in the internal focus of attention group also seem to retain improvements in between training sessions better than participants in the external focus of attention group. Improvements observed in participants in the internal focus of attention group, during the first training session, were retained in between training sessions as determined by the overall error observed at the beginning of each of the remaining training sessions. This finding suggests that focusing on the knee joint and improving participants' awareness of the optimal knee joint position might have helped participants to reduce the amount of hyperextension during training session and most importantly to retain the motor behavior in between training sessions.

Previous studies addressing correction of knee hyperextension have shown that gait patterns tend to be overcorrected after using verbal feedback with observation gait analysis (68), and maintained within a more normal extension angle (+/- 5°) after using real-time biofeedback (80). The results of the present study show that after the 6 sessions of treadmill gait retraining, using internal and external focus of attention, participants reduced the amount of knee hyperextension during treadmill walking at posttraining (2-5 days after training), and 4-month follow-up evaluations (Figure 4.15). However, the reduction in knee hyperextension in the present study was still within knee extension (0-5°) values.

Related to **retention**, the reduction in knee extension range of motion during treadmill walking was retained at posttraining (short-term retention) and at 4-month follow-up (long-term retention). However, there were no significant differences in short and long-term retention between intervention groups. Previous studies on retention effects of learner's focus of attention instructions have shown inconclusive results after assessing retention one or two days after the acquisition phase. Some studies have shown that learners receiving external focus of attention instructions retained improvements observed during training better than participants receiving internal focus of attention instructions in balance tasks (23, 35, 36), upper extremity tasks (41, 42, 86). Other studies have found no differences between focus of attention groups in balance tasks (31, 44), upper extremity tasks (45, 84, 87, 88) , and novel gymnast routine (94). Contrary to the present study where participants received six training sessions (with at least one day in between training sessions), previous studies have only included two or three training sessions in consecutive days. This difference between previous and the present study, helps to validate the retention effects observed in the present study. Motor learning literature has shown that even though there might be changes after a single session, the control of movement changes gradually as a function of practice and movement execution becomes less reliant on feedback as the central nervous system becomes more efficient in predicting the optimal pattern (98). Therefore, the greater number of practice sessions and time in between training sessions used in the present study show the results of a more consolidated learning process observed during the retention test.

While no previous studies on learner's focus of attention have assessed retention 4 months after training, previous studies by our group, aimed at reducing knee hyperextension gait patterns, showed retention of changes in knee kinematics at 1 month after training sessions using real-time biofeedback (80) and at 8 months after training using augmented kinematic feedback linked to an internal and external focus of attention (Chapter 3). The retention results of the present study confirm previous findings indicating the beneficial effect of treadmill gait retraining programs for correcting knee hyperextension gait patterns in young women. The lack of significant differences in long-term retention between intervention groups might be due to the sample size used in the present study. Using the sample variability observed in this study and moderate effect size (.5), a post hoc power analysis reported 70% power. In order to obtain 90% power, we require a sample size of 23 subjects per group. It is not known if these changes persist beyond the 4-month follow-up included in this study.

Related to **transfer**, proficiency in controlling knee hyperextension patterns was partially transferred to overground walking at posttraining (Figure 4.15) in both intervention groups. However, there was no significant difference in transfer to overground walking and obstacle crossing between intervention groups. Previous studies assessing transfer effects of focus of attention instructions have modified the throwing distance (84, 87, 88), increase the speed (34) or to use the opposite foot and arm movements used during acquisition (94). In our previous study using biofeedback and focus of attention instructions to correct knee hyperextension gait patterns in young women (chapter 3) transfer was tested using a similar activity performed in a different environment (overground walking). In the present study transfer was assessed using a similar activity (overground walking) and a different activity (obstacle crossing) in an environment different that the one used during training.

Research has suggested that instructions that induce an external focus of attention would lead to more effective learning by promoting the utilization of automatic and natural control mechanisms instead of self-regulatory processes in attempts to control one's movements (5, 9, 23). Underlying this hypothesis it is thought that by promoting automaticity of movement control during treadmill gait retraining program, women in the external focus of attention group would be able to control tibiofemoral sagittal alignment using strategies that might be less affected by conditions that differ from those under which the skill was practiced. Then, the improved alignment could be transferred to activities or environment less similar to the ones used during training. In the present study transfer of learning was assessed using a similar activity performed in a different environment (e.g. overground walking), and an untrained activity performed in a different environment (e.g. overground obstacle crossing). Research has shown that even though the mechanics of treadmill and overground walking are very similar (99, 100), individuals tend to modify their muscle activation patterns that may lead to different motor strategies (99). In addition, treadmill walking seems to provide people with strong contextual cues (mainly mismatch between vision and perception) that are unusual during overground walking and therefore the nervous system may link the adapted pattern to this particular context (82). The results of the present study showed that participants in both intervention groups were able to partially transfer modified knee kinematic changes to less similar activities performed in different environment that the one used during training. However, contrary to what was hypothesized in the present study, there was no difference between intervention groups. Research on transfer of learning has suggested that human motor behavior is directed and motivated by performance demands and that transfer occurs within performance as learning is inconsequential unless it positively influences behavior at the time of performance (101) . This view might explain why participants in the internal focus of attention group showed better transfer than participants in the external focus of attention group in the present study. By being asked to think about the feeling from their knees during training, participants in the internal focus of attention group were asked to place demands on their sensory information processing during each practice trial which in turn contributed to transfer the ability to control the knee joint desirable position to less similar activities than the activity where training took place. Participants in the external focus of attention group, on the other hand, were asked to focus on the wand's angle which was not present during the transfer test; therefore reducing the possibilities of transfer.

Overall, the results of the present study showed that participants in both intervention groups were able to partially transfer modified knee kinematic changes to overground walking. This finding provides evidence of the possibility of behavioral change and the ability to successfully apply modifications that took place during training to everyday activities (e.g. overground walking). In addition, the reduction in overall error (RMSE) and knee extension range of motion values observed during overground walking at posttraining seem to be retained during overground walking at 4-month follow-up.

Conclusions

The results of the present study indicate that there were not differences in learning acquisition, short and long-term retention, and transfer to overground walking and obstacle crossing between intervention groups. It is not known if these changes persist beyond the 4-month follow-up included in this study.

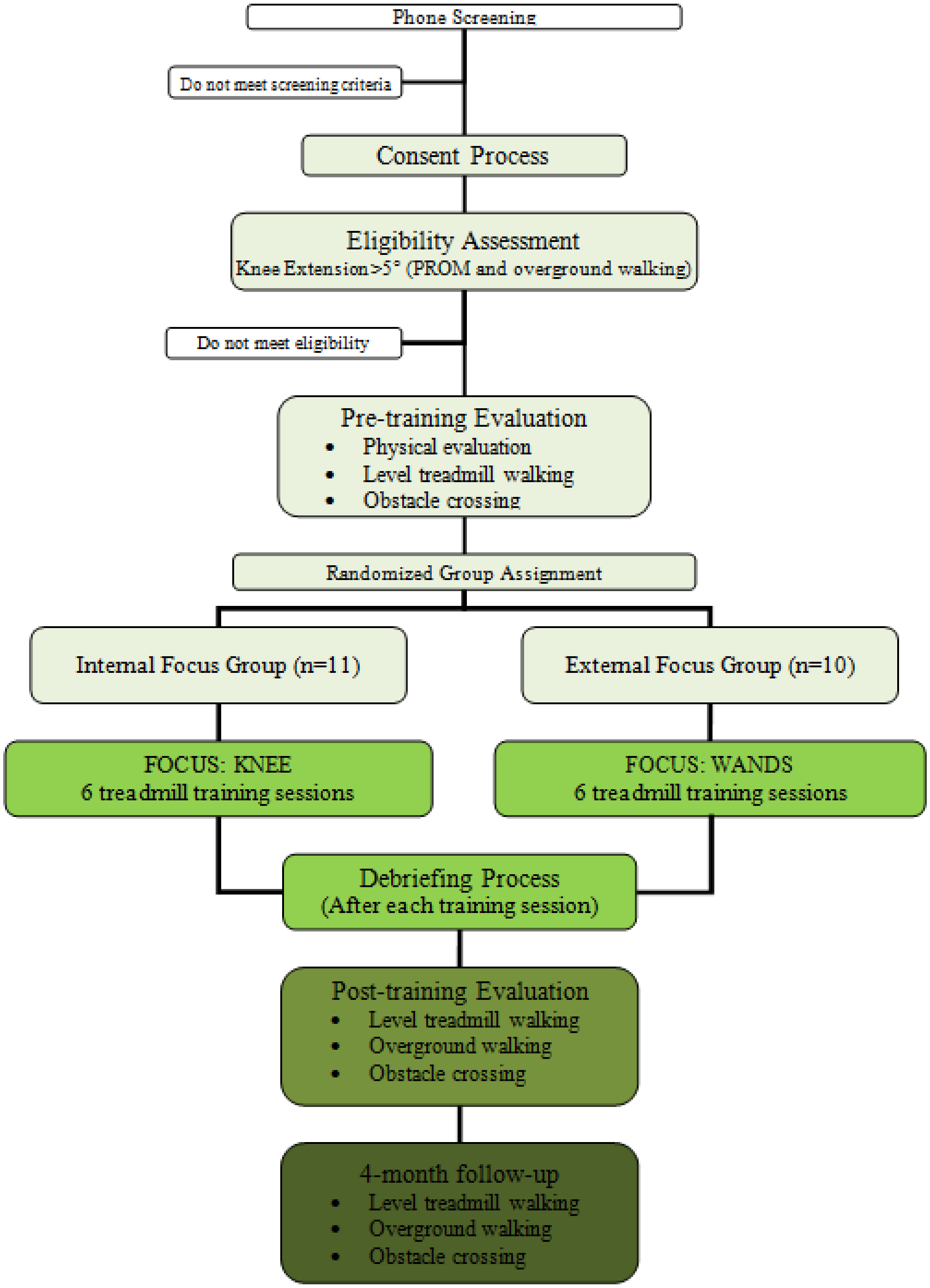


Figure 4.1 Flow diagram of intervention.

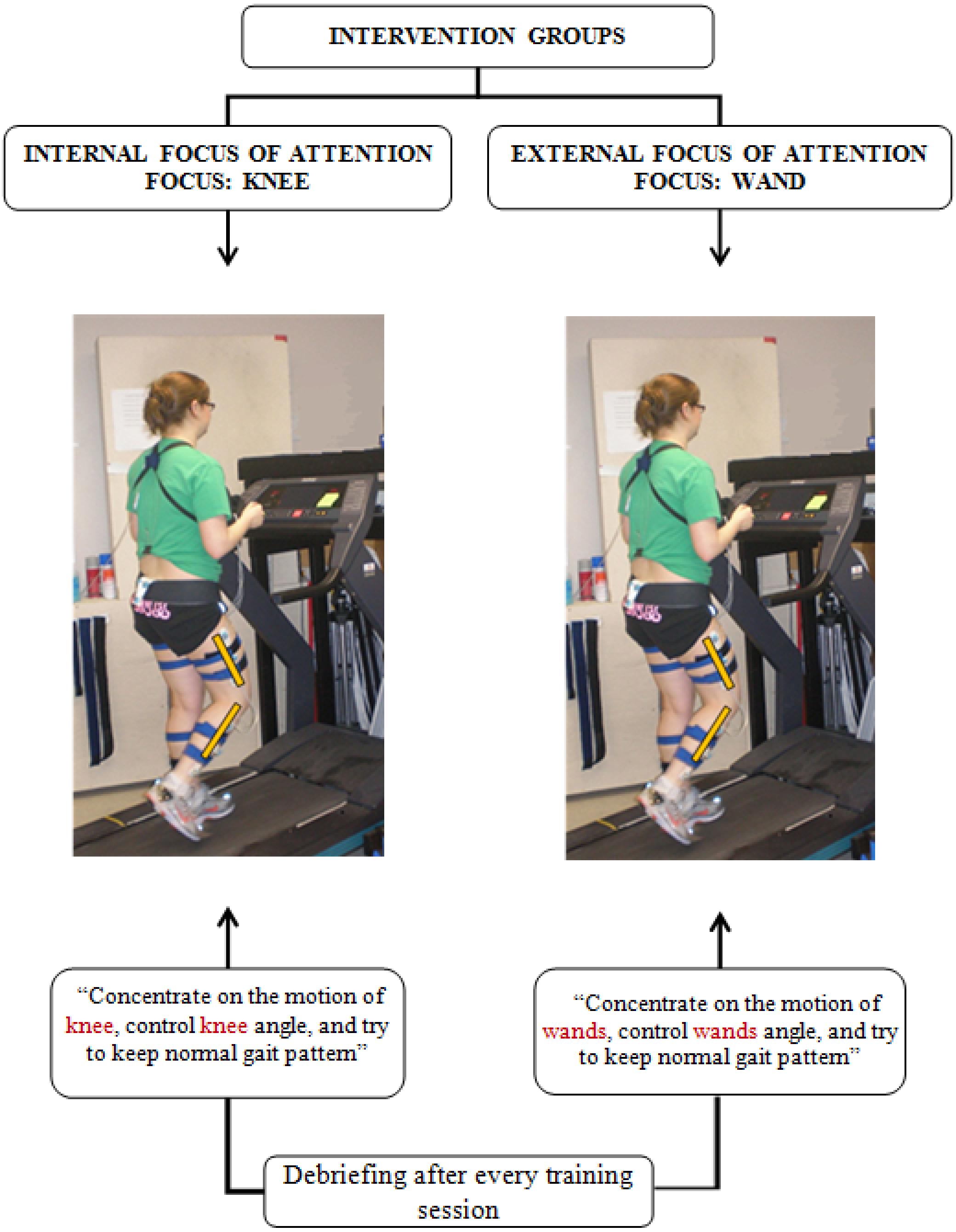
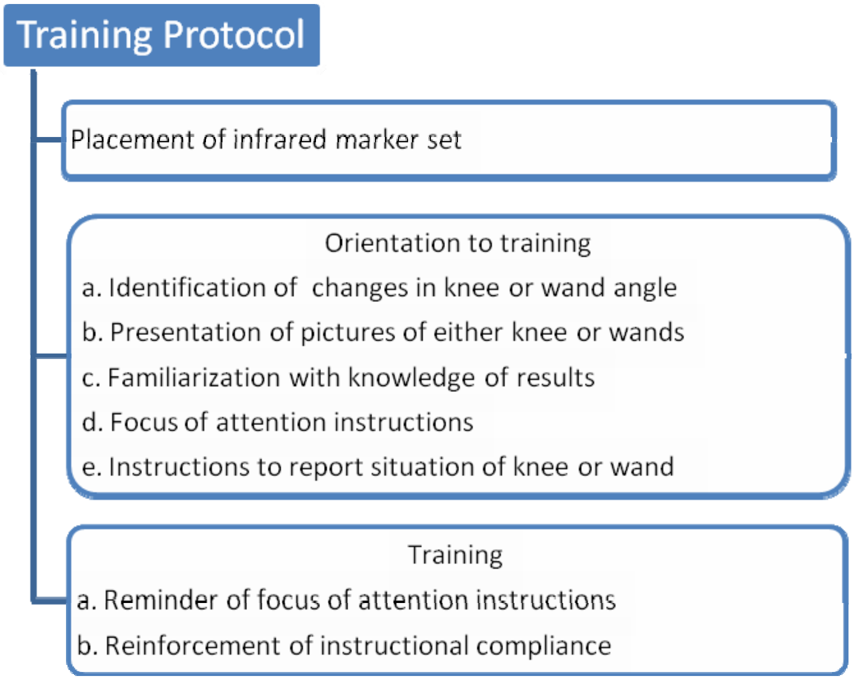


Figure 4.2 Participants in both groups received attentional instructions and underwent a debriefing process after each training session.



Training Protocol

Placement of infrared marker set

Orientation to training

a. Identification of changes in knee or wand angle

b. Presentation of pictures of either knee or wands

c. Familiarization with knowledge of results

d. Focus of attention instructions

e. Instructions to report situation of knee or wand

Training

a. Reminder of focus of attention instructions

b. Reinforcement of instructional compliance

Figure 4.3 Training protocol.

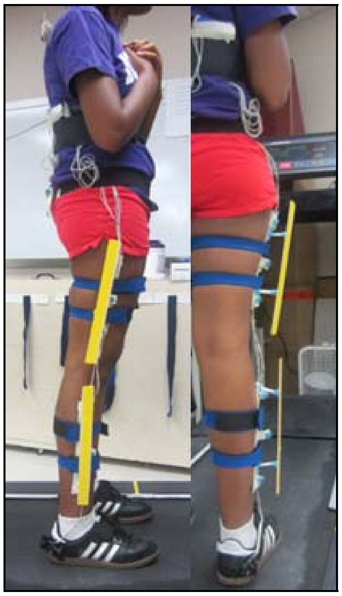


Figure 4.4 Bright color extensions (off-set by 5 cm) were attached to orthoplast sticks that hold infrared markers on legs and tights.

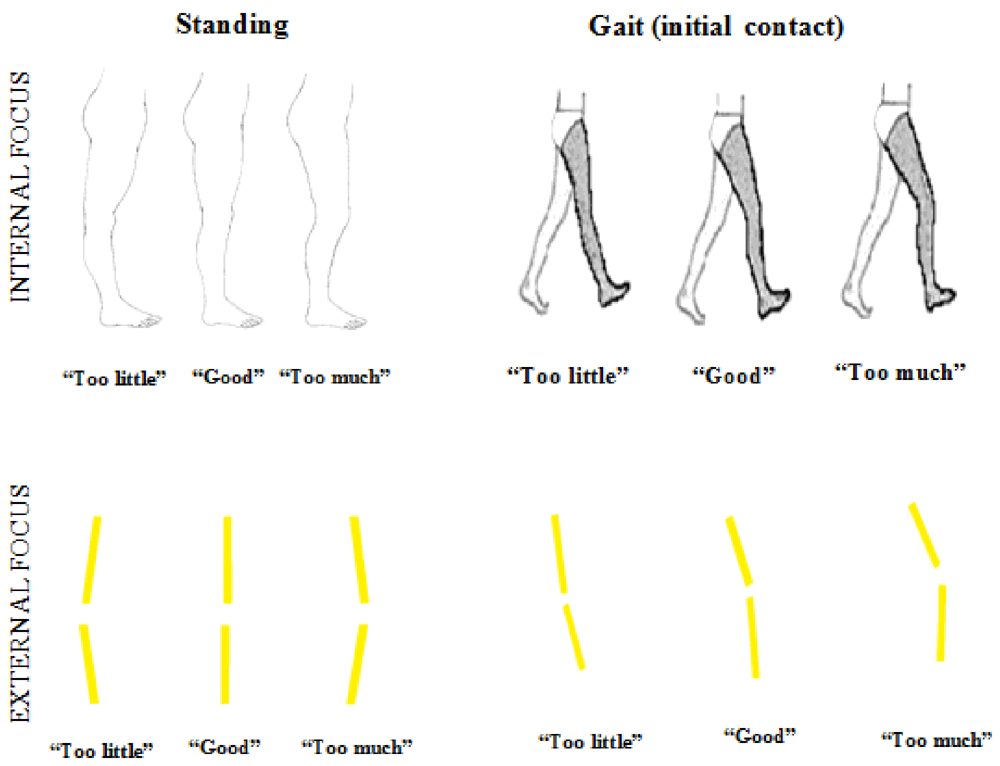


Figure 4.5 Images that were shown to participants, in the internal or external focus of attention groups, who demonstrated the greatest amount of knee hyperextension in the right knee during initial contact phase of gait cycle. Images of standing position were shown first. Images of gait stayed on display during the training session.

Figure 4.6 Organization of training sessions.

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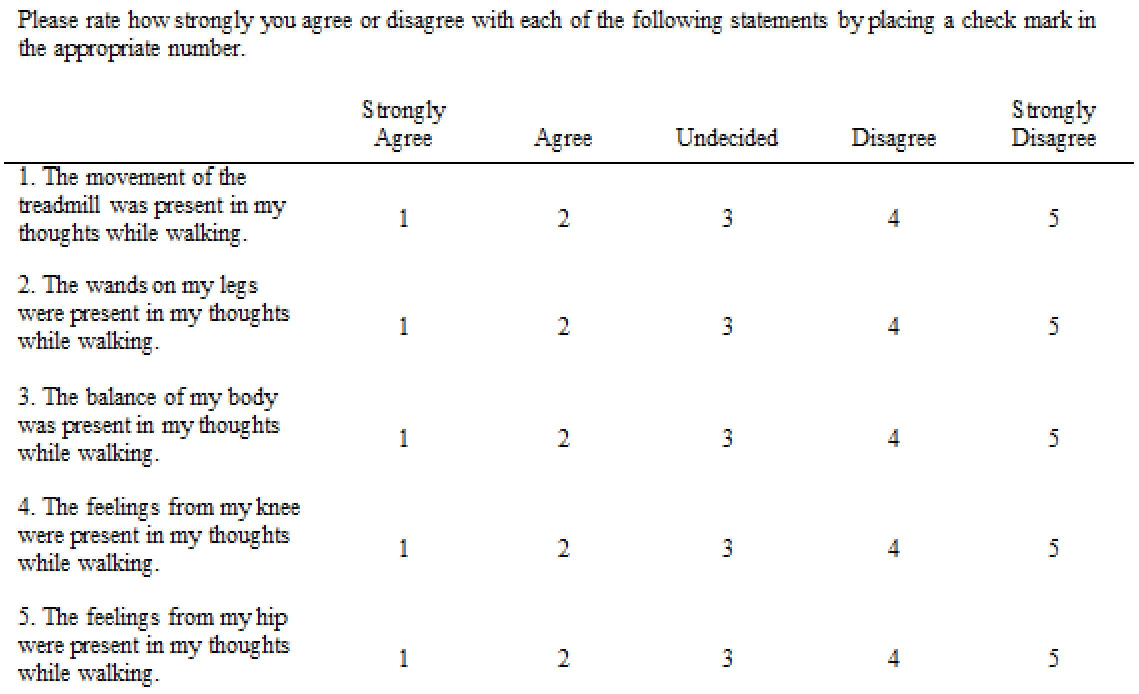
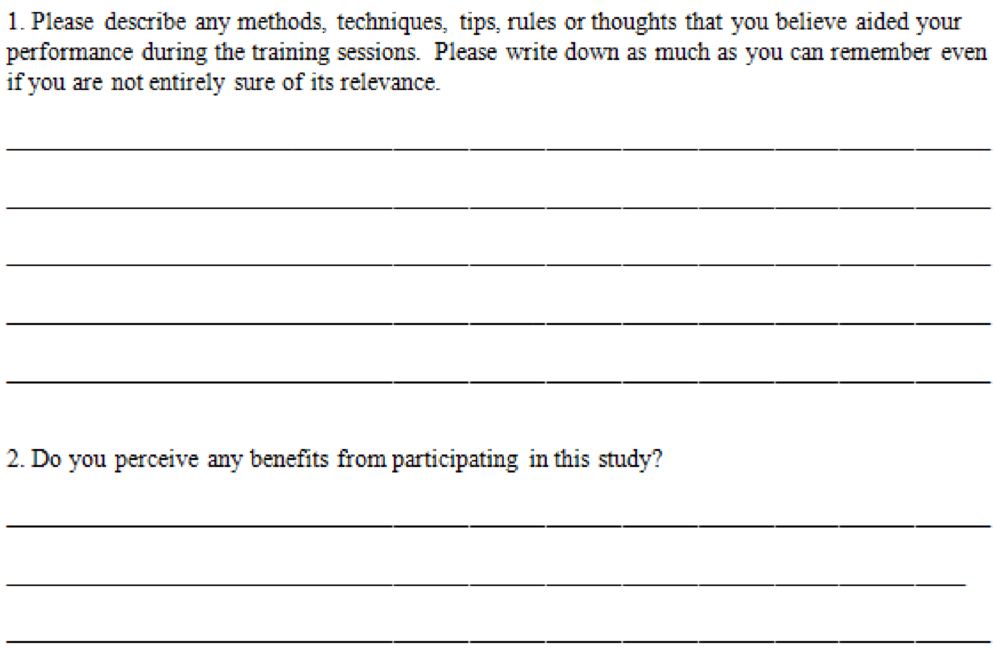
* indicates when knowledge of results were provided.



Please rate how strongly you agree or disagree with each of the following statements by placing a check mark in the appropriate number.

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
1. The movement of the treadmill was present in my thoughts while walking.	1	2	3	4	5
2. The wands on my legs were present in my thoughts while walking.	1	2	3	4	5
3. The balance of my body was present in my thoughts while walking.	1	2	3	4	5
4. The feelings from my knee were present in my thoughts while walking.	1	2	3	4	5
5. The feelings from my hip were present in my thoughts while walking.	1	2	3	4	5

Figure 4.7 Likert scale format questionnaire used for debriefing process.



1. Please describe any methods, techniques, tips, rules or thoughts that you believe aided your performance during the training sessions. Please write down as much as you can remember even if you are not entirely sure of its relevance.

____

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____

2. Do you perceive any benefits from participating in this study?

____

____

____

Figure 4.8 Open-ended questions used to debrief participants in both intervention groups.

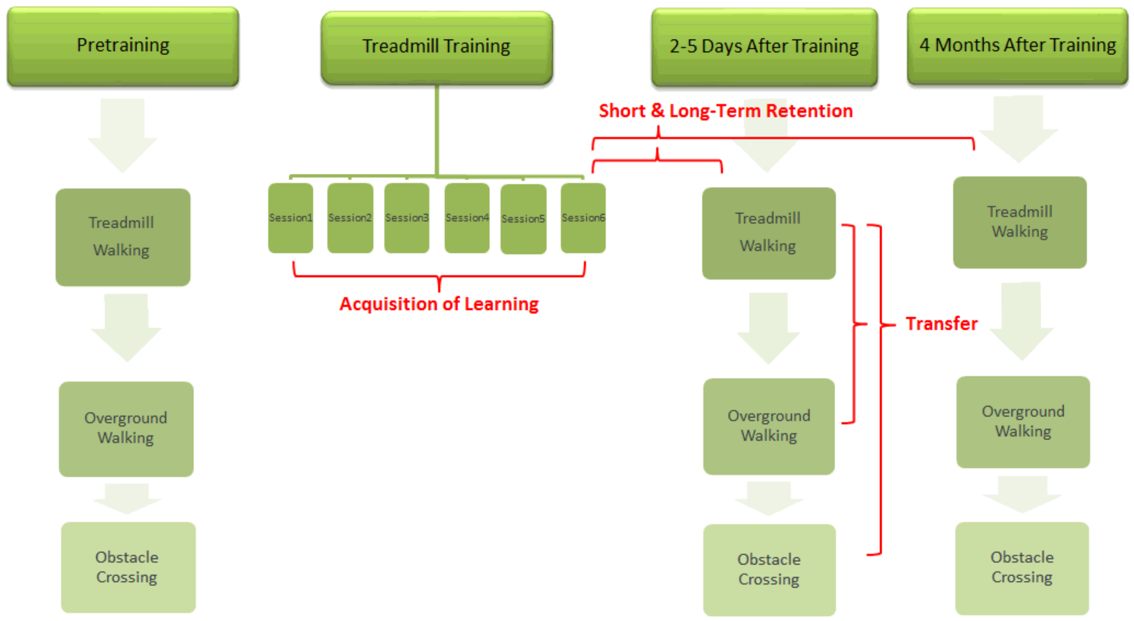
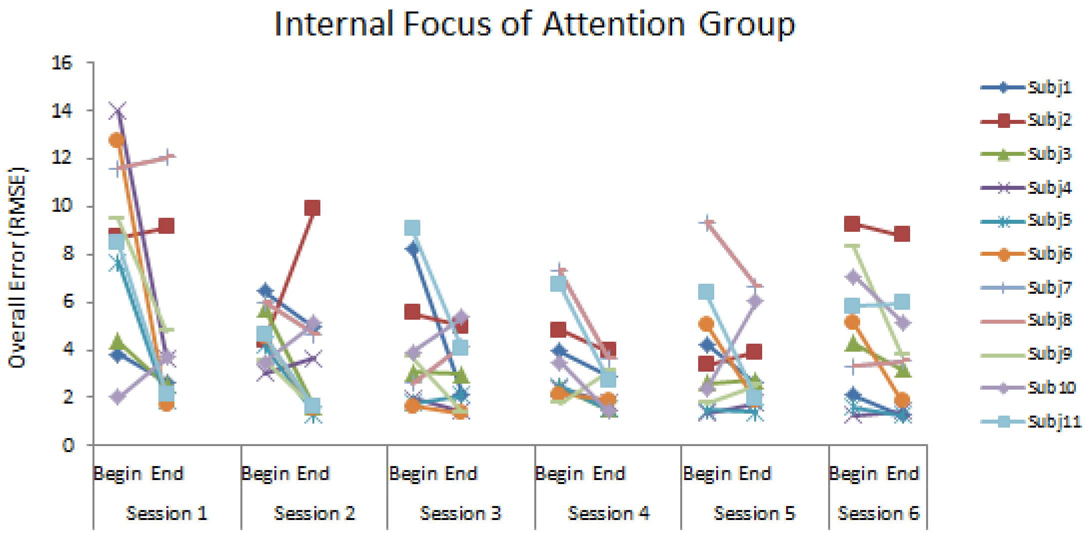


Figure 4.9 Diagram shows how data was analyzed to assess acquisition, retention, and transfer effects of treadmill training program.

Table 4.1 Results of the debriefing process

	Internal Focus / External Focus (%)				
	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
The movement of the treadmill was present in my thoughts while walking.	5.5 / 16	32.7/42	12.7 / 6	34.6 / 26	14.6 / 10
The wands on my legs were present in my thoughts while walking.	0 / 40	20 / 46	9.1 / 12	50.9 / 2	20 / 0
The balance of my body was present in my thoughts while walking.	3.6 / 2.2	54.5 / 38	20 / 14	10.9 / 16	10.9 / 10
The feelings from my knee were present in my thoughts while walking.	52.7 / 8	38.2 / 32	7.3 / 32	1.8 / 16	0 / 12
The feelings from my hip were present in my thoughts while walking.	1.8 / 8	16.4 / 18	7.3 / 16	40 / 38	34.6 / 20



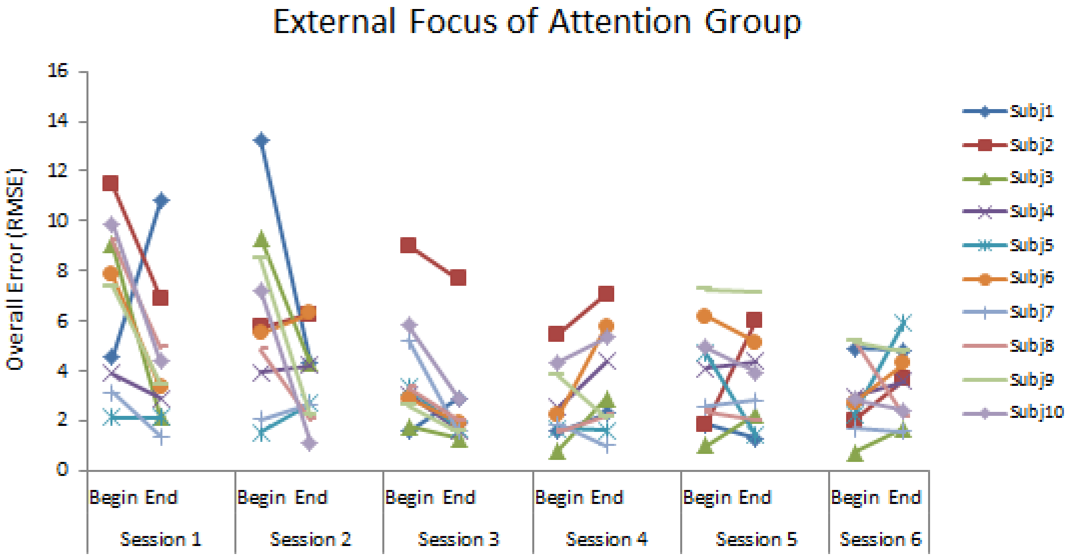


Figure 4.10 Individual overall error at the beginning and end of six training sessions.

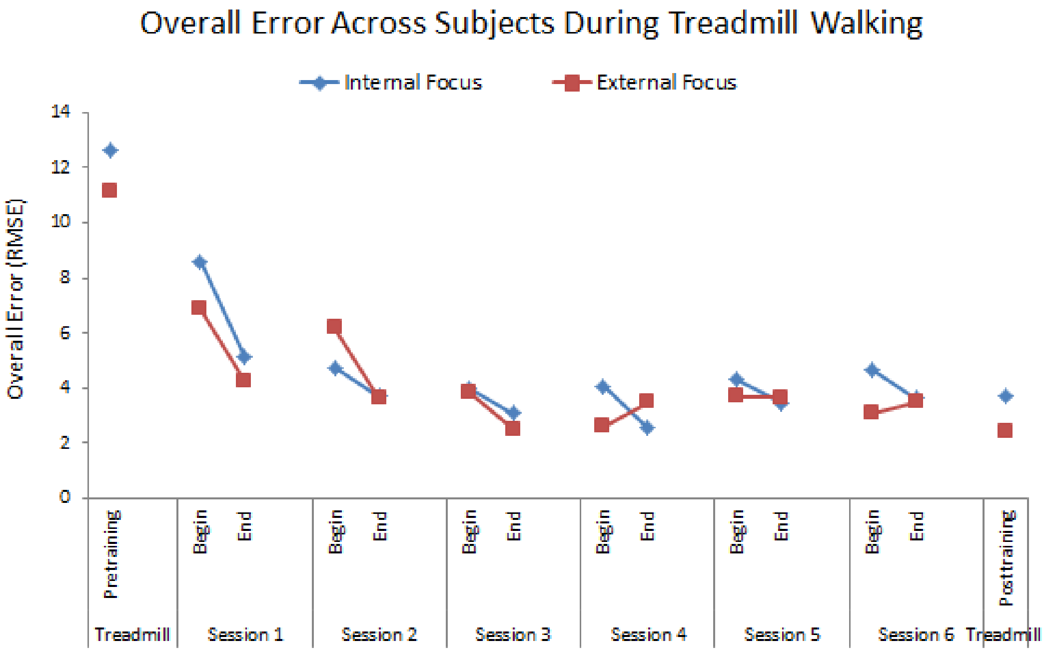


Figure 4.11 Mean overall error across subjects during treadmill walking at pretraining, training sessions (Session 1-6), and posttraining.

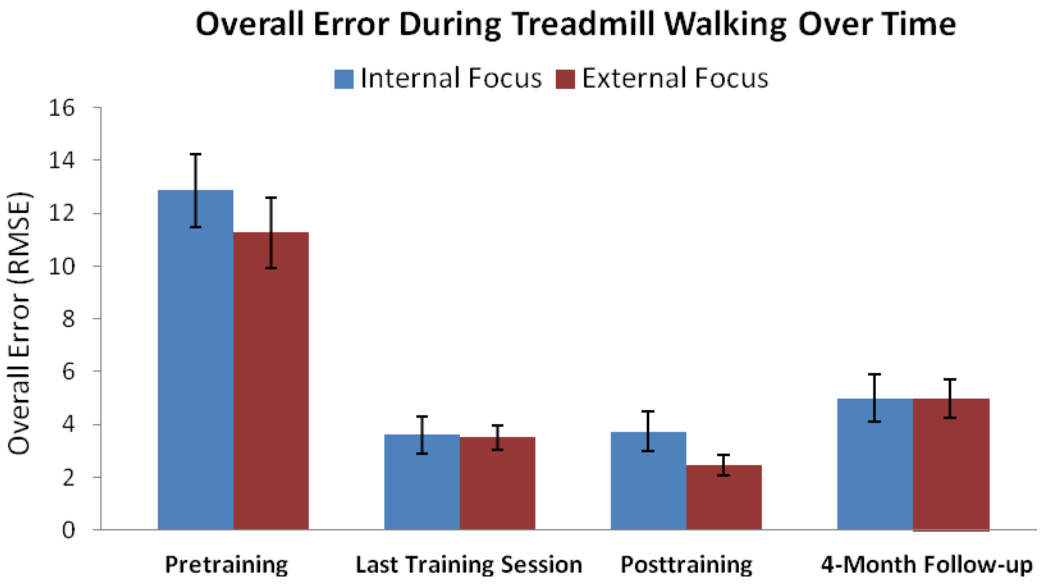


Figure 4.12 Average overall error (RMSE) and standard error values across subjects during treadmill walking at pretraining, last training session, posttraining (2-5 days after training), and 4-month follow-up evaluations. There was a significant reduction of knee hyperextension gait patterns over time.

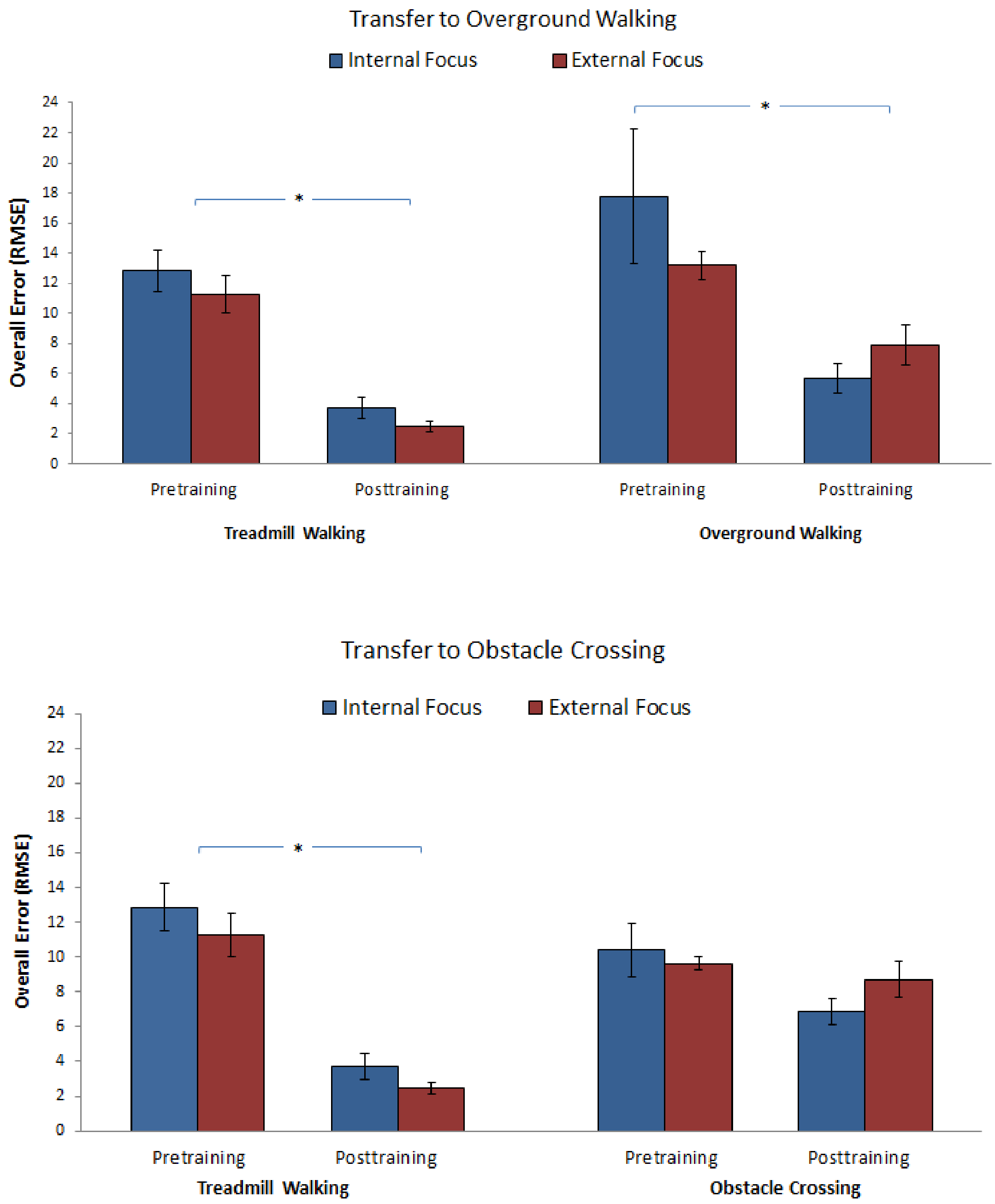


Figure 4.13 Top graph shows average overall error and standard error during treadmill and overground walking at pretraining and posttraining. There was no significant difference (p=.36) in transfer to overground walking between intervention groups. Bottom graph shows average overall error and standard error during treadmill and overground walking at posttraining. There was no significant difference (p=.13) in transfer to obstacle crossing between intervention groups.

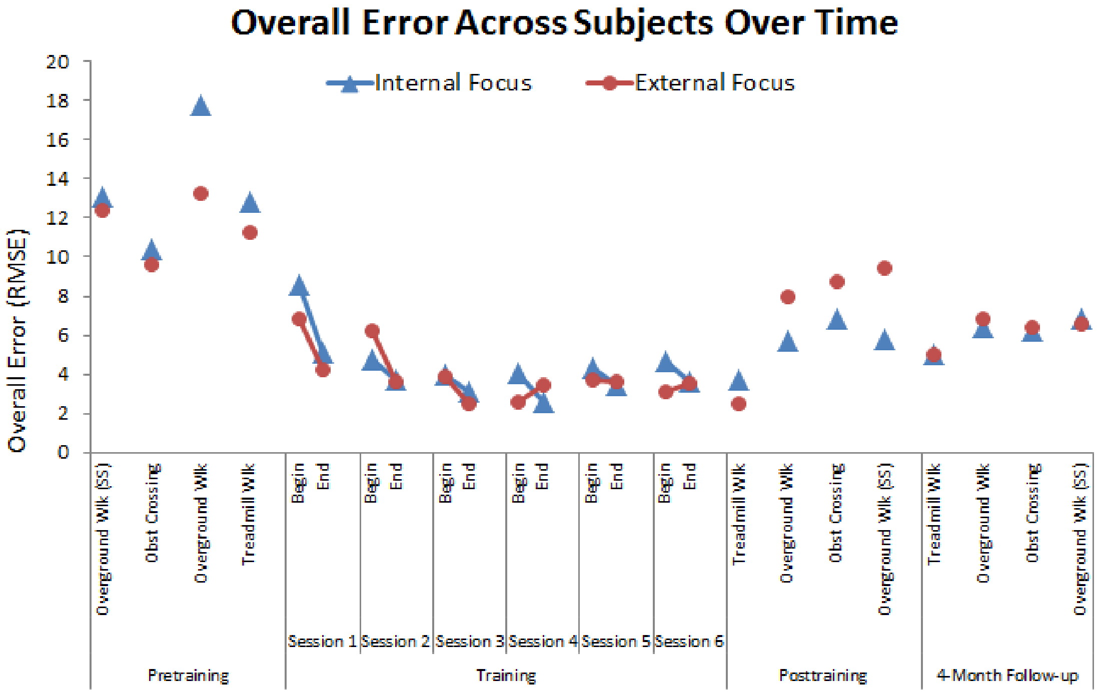


Figure 4.14 Overall error (RMSE) values across subjects in both intervention groups at pretraining, treadmill training sessions (1-6), posttraining, and 4-month follow-up.

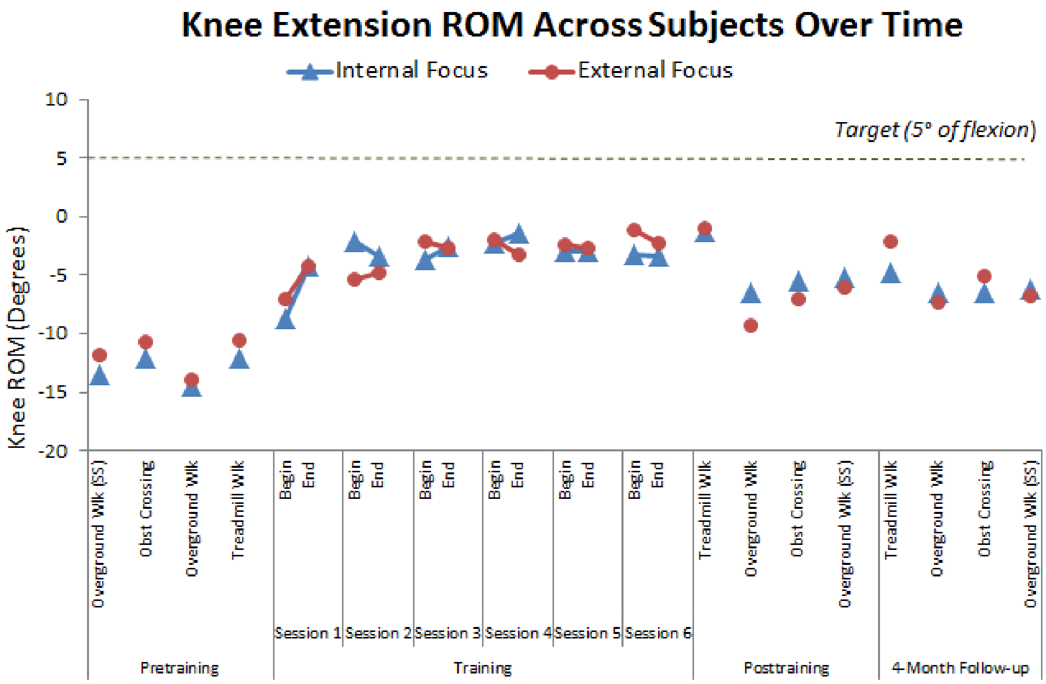


Figure 4.15 Knee extension range of motion values across subjects in both intervention groups at pretraining, treadmill training sessions (1-6), posttraining, and 4-month follow-up.

CHAPTER 5

CONCLUSIONS

Clinicians working on interventions that require learning or modifying motor skills often find that improvements observed during training are not sustained and do not transfer to very similar tasks. How well skills are retained over time (retention) and how well they can be used in new situations the learner may encounter (transfer) are important concerns in motor learning as both, retention and transfer, are indicators of relatively permanent changes in movement capabilities. Therefore, it is beneficial to find strategies that facilitate effective learning. Research in motor control and learning suggests that augmented kinematic feedback and strategies that manipulate the focus of attention of the learner may influence learning of motor skills. However, research on the implications of these strategies in rehabilitation has been minimal.

The purpose of these studies was to investigate acquisition, retention, and transfer effects of a treadmill gait retraining programs. The retraining programs manipulated augmented kinematic feedback and learner's focus of attention, in training programs aimed at correcting knee hyperextension gait patterns in healthy young women. Specific aims in the studies and outcomes are presented below.

Specific Aim 1

To investigate the efficacy of a treadmill gait training program using real-time kinematic feedback for correcting knee hyperextension in asymptomatic females.

Hypothesis 1a:

Treadmill training using real-time feedback will facilitate the reduction of knee hyperextension during the acquisition phase.

Supported: Participants decreased knee hyperextension range of motion during the acquisition phase of a treadmill gait retraining using real-time kinematic feedback. The potential of real-time kinematic biofeedback to foster subtle changes in gait patterns that otherwise may be difficult to perceive was underscored.

Hypothesis 1b:

Treadmill training using real-time feedback will lead to improved control of knee hyperextension immediately following training and at a 1-month follow-up.

Supported: Significant reductions in knee hyperextension patterns were observed immediately and at 1 month following training. Gained proficiency in controlling knee hyperextension patterns during treadmill training was also evident for overground walking, in which visual cueing may be different. These results suggest the ability of treadmill gait training with real-time feedback to modify the motor program and transfer learning to overground walking.

Specific Aim 2

To examine if an external or internal focus of attention influenced the effectiveness of real-time visual biofeedback, during treadmill gait training for correcting knee hyperextension patterns, in young, asymptomatic, female subjects.

Hypothesis 2a:

Receiving treadmill gait training, with real-time biofeedback, will be more effective in improving performance during acquisition when the focus of attention is biased toward external rather than internal cues.

Not supported: While the treadmill gait training program showed significant reductions in knee hyperextension patterns during the acquisition phase, there were not significant differences between intervention groups.

Hypothesis 2b:

Participants in the external focus of attention group will show a better long-term retention of performance gains compared to participant in the internal focus of attention group.

Not supported: While the treadmill gait training program showed significant reductions in knee hyperextension patterns immediately following training and at 1 and 8-month follow-ups, there were not significant differences between intervention groups.

Specific Aim 3

To investigate the efficacy of a treadmill gait retraining program using learner's focus of attention instructions in correcting knee hyperextension in asymptomatic females.

Hypothesis 3a:

Women in the external focus of attention group will demonstrate greater acquisition of learning than women in the internal focus of attention group.

Not supported: There was a significant reduction in the knee overall error during training, there were not significant differences between intervention groups. There was a significant reduction in knee extension range of motion during treadmill walking after training.

Hypothesis 3b:

Women in the external focus of attention group will demonstrate greater short and long-term retention than women in the internal focus of attention group.

Not supported: The reduction in knee extension range of motion during treadmill walking was retained at posttraining (short-term retention) and at 4-month follow-up (long-term retention). However, there were not significant differences in short and long-term retention between intervention groups. The lack of significant differences in long-retention between intervention groups might be due to the sample size used in the present study.

Hypothesis 3c:

Women in the external focus of attention group will demonstrate greater percentage of transfer to untrained tasks than women in the internal focus of attention group.

Not supported: Proficiency in controlling knee hyperextension patterns was partially transferred to overground walking at posttraining in both intervention groups. Even though both intervention groups showed a similar reduction in the amount of overall error at posttraining treadmill walking, participants in the internal focus showed a significant smaller overall error (RMSE) and therefore greater percentage of transfer during overground walking at posttraining. Reduction in overall error (RMSE) and knee extension range of motion values observed during overground walking at posttraining seem to be retained during overground walking at 4-month follow-up. There was no significant difference in percentage of transfer to obstacle crossing (P=.08) between intervention groups.

Summary

The potential of real-time kinematic biofeedback to foster subtle changes in gait patterns was underscored. Gained proficiency in controlling knee hyperextension patterns during treadmill training was also evident for overground walking. The results of this sequence of studies support the effects of real-time biofeedback in facilitating the acquisition and retention of proficiency in controlling knee hyperextension gait patterns, documenting that the retention is sustained for up to 8 months. However, there were not significant differences when augmented feedback was linked to groups that had a different focus of attention. It is not known if participants actively switched to an external focus of attention despite the instructions provided during training. When real-time biofeedback was not included in the training program there were no significant differences in acquisition, short and long-term retention, and percentage of transfer to obstacle crossing between intervention groups. Participants in the internal focus of attention group showed a greater percentage of transfer to overground walking. Participants in both, internal and external focus of attention, groups showed significant reduction in knee extension ranger of motion immediately after training and at 4-month follow-up. However, participants under the training program using performer's focus of attention instructions did not achieve the level of progress observed in participants using real-time kinematic feedback.

It is not known if these changes persist beyond the 8-month follow-up included in this study. In addition, while the results demonstrate that knee hyperextension may be reduced over time, we do not know how the training affected participants’ gait pattern outside the laboratory.

APPENDIX

KNEE KINEMATICS DURING FUNCTIONAL ACTIVITIES IN HEALTHY WOMEN WITH KNEE HYPEREXTENSION

Introduction

Abnormal knee kinematics can result in excessive loading of structures of the knee joint, such as menisci, ligaments, or cartilage. Associated change to these structures, due to the abnormal stress, can be detrimental to the integrity of the knee joint (56, 57). Normal standing posture of the knee in the sagittal plane consists of a vertically aligned femur and tibia, forming a 180 degrees angle. Movement of the knee into hyperextension (genu recurvatum) of more than 5° is associated with a ground reaction force vector that acts anterior to the knee joint, placing substantial increased stress on the passive restraining structures that resist further knee extension.

Knee hyperextension implies increased stress to the posterior joint capsule of the knee (58) and to the anterior cruciate ligament (ACL) (54). Studies also point out that there is an increased contact stress on the anterior compartment of the tibial-femoral joint when the knee joint is extended (59). When tracking the motions of the knee under laboratory-controlled knee joint hyperextension experiments in human cadaver joints, high contact pressures were noted in the anterior compartment of the tibiofemoral joint due to the combined rolling and sliding of the femoral condyles on the anterior tibial plateau during hyperextension (63). Figure A.1 shows the contact pressure distribution in the anterior compartment of the knee noted in Myer's study (63).

Studies have also shown that women have a greater tendency towards knee hyperextension than men (65) and active young women with knee hyperextension are more susceptible to injury (62). Previous work aimed at determine the amount of knee hyperextension in women have focused on knee sagittal alignment during passive range of motion (PROM) and level ground walking. However, studies have not investigated knee sagittal plane kinematics during other activities of daily life that normally require full knee extension. Analysis of knee joint kinematic performance in women with knee hyperextension can add to our understanding of the knee joint quotidian demands in this population.

The purpose of this study was to investigate knee joint sagittal plane kinematics during: quite standing, level and sloped walking, stair climbing, obstacle crossing, and level and sloped running in women with asymptomatic knee hyperextension. It was hypothesized that women with knee hyperextension at PROM will show similar amount of knee hyperextension during level and sloped walking, stair climbing, obstacle crossing, and level and sloped running.

Methods

Subjects

Healthy female recreational runners, 18-39 years of age, with no history of lower limb surgery or cardiovascular, neurological or functional limitations took part in this study. Participants were screened and included in the study if they had asymptomatic knee hyperextension greater than 5° during passive range of motion and run or jog at least 5 miles per week. Knee hyperextension was measured in supine with the ankle resting on a 10-cm support, using standard goniometric techniques. Prior to participation, all subjects provided informed consent and the study protocol was approved by the University of Iowa's Institutional Review Board.

Testing Protocol

Participants underwent a physical and gait evaluation. The physical evaluation screened muscular strength in each subject's legs using standard techniques, and assessed general joint laxity using the Beighton and Horan Joint Mobility Index (BHJMI). Knee kinematic data was collected during over ground (standing, level walking, obstacle crossing, and stairs negotiation) and treadmill (level, incline, and decline walking and running) activities.

A 3-dimensional motion analysis system (Optotrak™, Northern Digital Inc., Waterloo, Ontario - Canada) was used to collect kinematic data during gait activities. Three non-collinear infrared markers were used to track each of the following body segments: feet, legs, thighs, pelvis, and trunk. Marker coordinate data were collected at 60 Hz and filtered at 6 Hz. To define the axes of each of the 8 segments, an anatomical model was created by digitizing standard bony landmarks: anterior and posterior superior iliac spines, greater trochanters, lateral and medial epicondyles, lateral and medial malleoli, posterior heel, second toe, the head of the fifth metatarsal, and C4 and L4 vertebrae. Kinematic data were calculated using Visual 3D (C-Motion, Germantown, MD).

After the physical evaluation and prior to the gait evaluation, set walking (1.3 m/s) and running (2.7 m/s) velocities were individually adjusted to each subject's leg length using the Froude ratio (V2/√gL) (102) in order to establish similar walking and running conditions and reduce variability among subjects.

Overground standing and walking

After asking participants to stand still for 1 second, participants were asked to walk several times along an 8-meter walkway. Each participant's estimated walking speed was monitored by the investigator using an overhead timing chain. Kinematic data on 5 gait cycles were collected. A gait cycle was defined from initial contact to initial contact of the same foot.

Obstacle crossing

Subjects were asked to walk at a self-selected pace along an 8-m walkway and crossed a height-adjustable obstacle that was composed of a 1.5m long aluminum tube with a diameter of 1.5 cm placed across a metal frame. The tube was light and rigid so it would have dropped off the frame if contacted. Test conditions included crossing the obstacle at a height equivalent to 10% of each participant's leg length. Participants started walking approximately 4 m from the obstacle and continued walking for at least 2 m after the obstacle. Knee kinematics for the leading and trailing limbs during ten trials, five for each leg, were collected. A stride cycle was defined from initial contact before and push-off after crossing the obstacle.

Stairs negotiation

Participants were instructed to ascend the stairs at a self-selected pace, placing only one foot on each step. The experimental staircase consisted of three steps (step height 18 cm, tread length 28.5 cm). For each subject, stair climbing testing consisted of five ascending and five descending trials. Participants were instructed to use their preferred limb. During stair ascent, a stride cycle started with the push-off before foot contacted the first step and ended with the contact of the same foot on the third step. During stair descent, a stride cycle started with the push-off on the third step and ended with the push off of the same foot on the floor.

Level and sloped treadmill walking and running

The assessment of walking and running kinematics was conducted on a level, inclined (10%), and declined (-10%) treadmill using the same anatomical modeling approach and three-dimensional motion analysis system (Optotrak, NDI; Kistler) used during overground gait activities. Participants were asked to walk at their scaled speed during 5 minutes to get familiarized with the treadmill. After a 2-3 minutes break, participants were asked to walk on a level treadmill for 2 minutes, 10% inclined treadmill for 1 minute, level treadmill for 2 minutes, and 10% declined treadmill for 1 minute. After the declined treadmill walking, participants follow the same sequence for the running testing. The set running speed (2.7 m/s) velocity was also scaled to each subject's leg length using the Froude ratio (V2/√gL) (85, 102). Kinematic data was collected during the final 15 seconds of level, incline, and decline walking and running tasks.

Data Analysis

Descriptive statistics for age, height, weight, general joint laxity score, and passive range of motion were determined. Knee extension range of motion was the primary biomechanical measure. Sagittal plane knee extension values during overground and treadmill gait activities were determined using Visual 3D (C-Motion, Germantown, MD). Data obtained from a previous study were used to determine the appropriate sample size. This study showed a mean +/- SD of 8.8° +/- 2.4°, and 7.9° +/- 3.3 of peak knee extension for passive range of motion and overground walking, respectively. Based on previous study's mean difference (0.9° +/- 3.6°) in knee extension range of motion between testing conditions, we anticipated a mean difference in knee extension angle between PROM and tested activities of less than 2°. In order to obtain 90% (for a one-sided test with alpha = 0.05), a minimum sample size of 16 participants was required. To account for potential technical problems with the data collected, we recruited a sample size of 20.

The average peak knee extension range of motion was obtained for the standing trials. For the obstacle crossing and stair negotiation tasks, the average of three maximum knee extension angles during a stride cycle was acquired for each task. For the over ground walking, level and sloped walking, and level and sloped running trials, the average of three maximum knee extension angles over consecutive gait cycles was determined. Comparisons of peak knee extension values during ground and treadmill gait activities were made using linear mixed models for repeated measures. Significant results were explored using Tukey's Studentized Range follow-up test ($\alpha < 0.05$). All statistical testing were performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA). Level of significance was set at $p = .05$ for all analyses.

Results

A total of twenty healthy women (mean +/- SD age, 23 +/- 4.9; mass, 64.9 +/- 8 kg; height, 1.7 +/- 0.1 m) took part in this study. Descriptive statistics for age, height, weight, general joint laxity score, and walking and running estimated velocities are presented in Table A-1. The PROM assessment showed that 11 participants had greater knee extension in their right knee. There was no difference between knee PROM of right and left sides; therefore, data for both, right and left, sides were combined for further analysis. Mean +/- SD peak knee extension passive range of motion was -8.4º +/- 1.9º (range -6° to -14°). Mean +/- SD peak knee extension during overground walking was -8.9º +/- 4.2º (range -1° to -18°). Mean, standard deviation, and range knee extension values for functional activities during overground and treadmill are presented in Tables A.2 and A.3.

There was a significant difference between knee extension angle at PROM and obstacle crossing (leading limb) (p<.001) (CI= -8.1 - -2.5), incline walking (p=.0005) (CI= -6.6 - -1.03), and running activities (p<.001) (Figure A.2). The correlation coefficients between overground walking and obstacle crossing with the side of interest as the trailing limb and as the leading limb were r = 0.74 and 0.36, respectively. The correlation between overground walking and stepping down stairs was r = 0.53. The correlation between PROM and tested activities is presented in Table A.4.

Discussion

The purpose of this study was to investigate knee joint sagittal plane kinematics during level and sloped walking, stair climbing, obstacle crossing, and level and sloped running in women with asymptomatic knee hyperextension. It was hypothesized that women with knee hyperextension at passive range of motion will show a similar amount of knee hyperextension during functional activities. The results of the present study show that the magnitude of knee hyperextension seen at PROM was not different than during most of the activities assessed. Level and decline walking were the activities that were most associated with knee hyperextension.

The magnitude of knee hyperextension that we observed at passive range of motion and overground walking (mean +/- SD passive range of motion, -8.4º +/- 1.9º; overground walking, -8.9º +/- 4.2º) are similar to previous reports for this population (7.3°+/- 4.4°) (Noyes et al. 1996); (passive range of motion, 9.6º +/- 3.0º and overground walking, 8.7° +/- 3.3°) (Teran-Yengle et al. 2011); (passive range of motion, 8.8º +/- 2.4º and overground walking, 6.6° +/- 3.1°) (Chapter 3, Table 3.1).

The results of the present study showed considerable high values of knee hyperextension during quite standing. This finding represents a problem for women biased towards knee hyperextension as standing represents an activity where abnormal stress on restraining passive structures will be sustained. Knee sagittal plane alignment towards hyperextension has been found to be associated to high contact pressure in the anterior compartment of the tibiofemoral joint (63). Knee hyperextension during standing and associated high pressure in the tibiofemoral joint could potentially disrupt the cartilage's health. Studies have shown that increased stress in the tibiofemoral joint could affect the fluid flow and biosynthesis of chondrocytes and eventually lead to cartilage degeneration (103)

The unique findings of this study show that level walking and down-hill walking were the most problematic for subjects with knee hyperextension. Kinematic data in the present study showed peak knee extension values as high a 15° during level and downhill walking. Approximately 43% and 20% of the participants in this study showed between 8°- 10° and greater than 10° of knee hyperextension during walking as shown in Table A.3. While the mean values for overground and treadmill walking were quite similar, the association between these measures was not very strong. Studies conducted to compare treadmill versus overground walking in healthy young adults have suggested that even though limb kinematics and spatiotemporal gait parameters are maintained relatively constant, individuals tend to modify their muscle activation patterns and subsequently joint moments and powers (99, 100). The different muscle activation could explain the poor association found between knee extension range of motion at overground and treadmill walking.

The results of this study showed that both obstacle crossing and stepping down were also shown to be potentially problematic for individuals biased toward knee hyperextension. These finding tend to be lost when looking at previous research. Stepping off a curb is a common activity which has the potential to stress knee restraining structures. Running on level or inclined surfaces does not seem to be problematic for this population. While the majority of participants (65%) showed less than 5° of knee hyperextension during running activities, approximately 10% of the participants showed more than 10° of extension during slopped running. This finding represents a potential added problem for women with knee hyperextension patterns due to the potential repetitive stress that the tibiofemoral joint could experience during typical daily life gait activities.

The present study also showed an inverse relationship between knee extension range of motion at rest (PROM) and during some of the activities (standing, treadmill walking, and decline treadmill walking) (Table A.3). The authors wonder is there is an awareness based on maximum degree of knee hyperextension that leads women to control the degree of knee extension range of motion during daily activities. PROM is poorly associated with knee hyperextension during dynamic gait activities.

Conclusions

The results of the present study show that the magnitude of knee hyperextension seen at PROM was not different than during most of the activities assessed. Level and decline walking were the activities that were most associated with knee hyperextension. PROM is not a good predictor of the amount of knee extension during dynamic gait activities. Therefore, using PROM as an indication of knee extension range of motion during activities might be problematic.

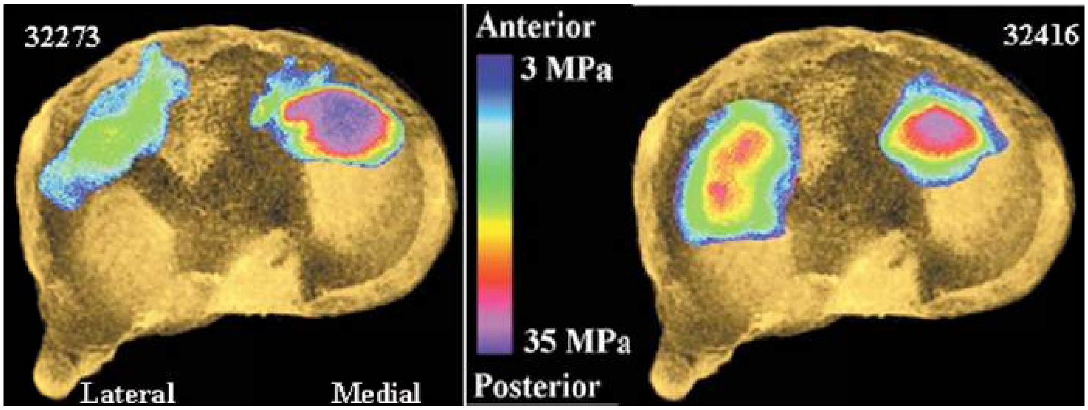


Figure A.1 Figure taken from Meyer EG, Baumer TG, Haut RC. Pure passive hyperextension of the human cadaver knee generates simultaneous bicruciate ligament rupture. J Biomech Eng. 2011 Jan;133(1):011012. Figure shows contact pressure distribution in a laboratory-controlled knee joint hyperextension experiments in human cadaver joints. High contact pressure in the anterior compartment of the tibiofemoral joint was noted.

Table A.1 Descriptive statistics across 20 female participants

	Average	SD	Max	Min
Age	23.0	4.9	36.0	18.0
Pain Rating	0.8	1.2	3.0	0.0
Height (m)	1.7	0.1	1.8	1.6
Weight (Kg)	64.9	8.0	79.0	51.0
Joint Laxity Score	2.9	1.3	5.0	0.0
Right Leg length (cm)	80.1	5.3	90.0	71.6
Left Leg length (cm)	80.2	5.3	90.0	72.0
Walking Speed (m/s)	1.3	0.0	1.4	1.3
Running Speed (m/s)	2.7	0.1	2.9	2.5

Table A.2 Descriptive statistics during overground and treadmill (TM) activities

	Mean	Standard Error	Confidence Interval		Range	
			Lower	Upper	Min	Max
PROM	-8.43	0.7	-9.8	-7.1	-14.0	-6.0
Standing	-8.94	0.7	-10.3	-7.6	-17.7	-0.1
Ground Walking	-7.37	0.7	-8.7	-6.0	-14.5	7.5
Obstacle (lead)	-3.13	0.7	-4.5	-1.8	-15.4	8.8
Obstacle (trail)	-7.82	0.7	-9.2	-6.5	-13.0	5.5
Step Down	-5.84	0.7	-7.3	-4.4	-14.9	-0.8
TM Walking	-7.99	0.7	-9.4	-6.6	-13.5	2.0
Incline TM Walking	-4.59	0.7	-6.0	-3.2	-12.9	8.8
Decline TM Walking	-7.64	0.7	-9.0	-6.3	-6.5	10.1
TM Running	1.08	0.7	-0.3	2.5	-16.6	3.6
Incline TM Running	-0.34	0.7	-1.7	1.0	-11.8	8.7
Decline TM Running	-3.93	0.7	-5.3	-2.6	-12.7	6.4

Table A.3 Percentage of knees showing hyperextension during gait activities

	PROM	Walk	Walk Up	Walk Down	Run	Run Up	Run Down
> -5°	0%	10%	40%	18%	83%	80%	65%
-5° to -7°	38%	28%	35%	20%	18%	8%	18%
-8° to -10°	48%	43%	15%	40%	0%	10%	10%
< -10°	15%	20%	10%	23%	0%	3%	8%

Table A.4 Pearson Correlation Coefficients (r) among PROM and gait activities

	PROM	**Standing**	**Walking**	**Obst. Crossing (Lead)**	**Obst. Crossing (Trail)**	**Step Down**	**TM Walking**	**Incline Walk**	**Decline Walk**	**Run**	**Incline Running**
Standing	-0.20	1									
Walking	0.16	0.21	1								
Obst. Crossing (Lead)	0.12	0.24	0.21	1							
Obst. Crossing (Trail)	0.20	0.24	0.56	0.35	1						
Step Down	0.01	0.25	0.44	0.31	0.60	1					
TM Walking	-0.17	0.02	0.49	-0.14	0.29	0.07	1				
Incline Walk	-0.01	0.18	0.31	0.56	0.04	-0.01	0.15	1			
Decline Walk	-0.43	0.53	0.19	0.26	0.18	0.03	0.28	0.61	1		
Run	0.14	-0.31	0.40	-0.04	0.00	0.04	0.28	0.23	-0.11	1	
Incline Running	0.39	-0.39	0.32	0.01	-0.15	-0.13	0.02	0.25	-0.24	0.71	1
Decline Running	-0.01	-0.18	0.37	-0.01	0.07	0.02	0.37	0.01	0.07	0.59	0.31

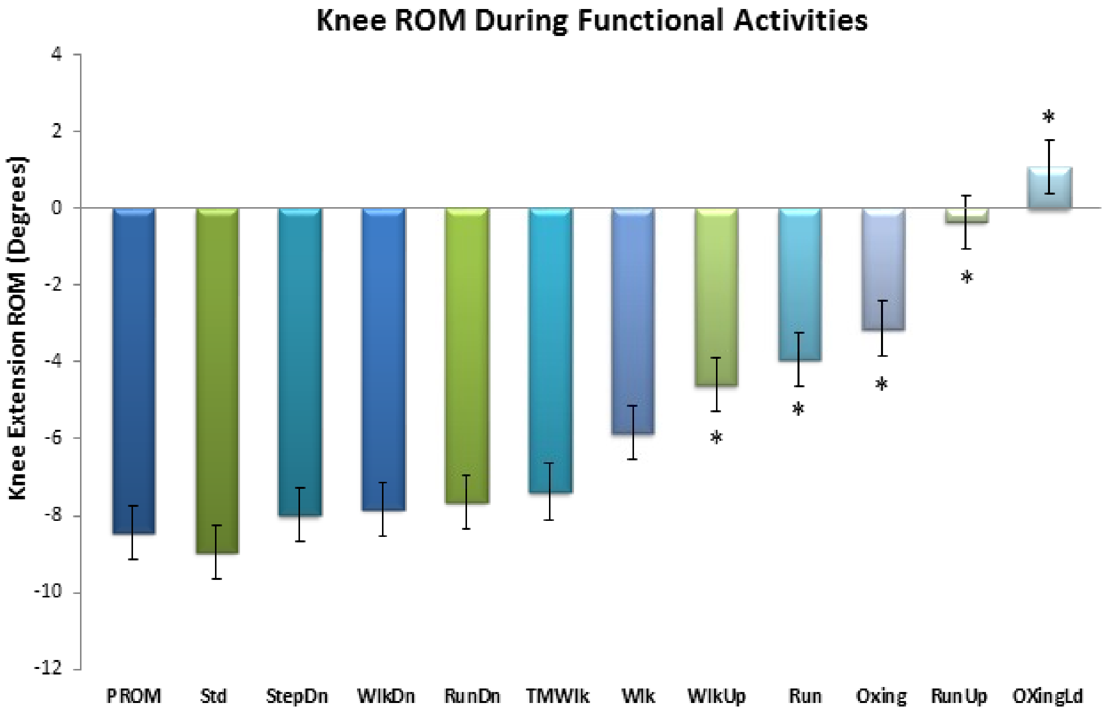


Figure A.2 Mean knee extension ROM with standard error during PROM, Standing (Std), Step Down Stairs (StepDn), Decline Walking (WlkDn), Decline Running (RunDn), Treadmill Walking (TMWlk), Overground Walking (Wlk), Incline Walking (WlkUp), Running (Run), Trailing Obstacle Crossing (OCrossTr), Incline Running (RunUp), and Leading Obstacle Crossing (OCrossLd). Asterisks (*) in figure indicate significant differences between knee extension range of motion during PROM and tested activity.

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