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THE EFFECTS OF NEUROMUSCULAR TRAINING ON THE GAIT PATTERNS OF ACL-DEFICIENT MEN AND WOMEN

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Abstract

Background—Anterior cruciate ligament rupture is the most common knee ligament injury sustained by active individuals, and the relative injury risk is sex-specific. Women not only demonstrate an increased risk for injury, but also a poorer response following ligament rupture. Perturbation training has shown positive results in healthy females, but gender-specific responses to training after injury have not been evaluated. The purpose of this investigation was to describe the effects of perturbation training on the gait characteristics of male and female non-copers.

Methods—Biomechanical data were collected before and after training on 12 male and nine female non-copers using standard motion analysis techniques. Subjects walked at a consistent, self-selected speed over an embedded force plate. Data from both limbs were post-processed and analyzed using a mixed model analysis of variance and minimal clinically important differences to compare the limb behaviors of men and women.

Findings—Prior to training, only women demonstrated significant hip joint excursion asymmetry (ES = 1.03; $P = 0.009$). Minimal clinically important difference values showed the involved limb of the women had reduced hip and knee flexion angles and moments, truncated knee excursions, and increased hip excursions when compared to their own uninvolved limb and the limbs of the male non-copers. Following training, only knee extensor moment values exceeded the minimal clinically important differences in the women.

Interpretation—Female non-copers demonstrated unique movement strategies following injury and perturbation training. Women may be a meaningful subgroup of non-copers, and future investigations should consider the effects of gender in the outcomes of non-copers.

Keywords

anterior cruciate ligament injury; gait; neuromuscular training; gender differences

Introduction

Neuromuscular training is a type of physical therapy intervention advocated to mitigate movement pattern deficits and abnormalities in a variety of patient populations. In the world

of sports orthopedics, the efficacy of neuromuscular treatment paradigms has been evaluated for the purposes of injury prevention, performance enhancement, and rehabilitation following injury or surgery. Following anterior cruciate ligament (ACL) rupture, abnormal movement patterns and neuromuscular behaviors are commonly found in those athletes with recurrent knee instability, where there is a subluxation of the tibia on the femur (Rudolph et al., 2001, Rudolph et al., 2000, Rudolph et al., 1998). These individuals, classified as non-copers, demonstrate asymmetrical movement strategies, including reduced sagittal plane knee excursions (Rudolph et al., 1998) and knee moments (Alkjaer et al., 2003, Rudolph et al., 1998) and increased hip moments on the uninvolved side during gait (Rudolph et al., 2001). Surgical reconstruction alone does not fully abate these aberrant gait patterns (Hartigan et al., 2009) and non-copers also demonstrate a reduced ability to return to sport following ligament reconstruction (Hartigan et al., 2010). Current physical therapy practice guidelines for knee ligament sprains now advise supplementing traditional strength training with neuromuscular training as a means to improve function and mitigate abnormal movement (Logerstedt et al., 2010). Expectedly, researchers have begun to evaluate the efficacy of varied neuromuscular training regimens in promoting function and restoring normal, symmetrical movement patterns in these athletes.

Perturbation training is a form of neuromuscular training designed to improve the dynamic stability of the knee through the timely co-activations of surrounding musculature (Fitzgerald et al., 2000c, Fitzgerald et al., 2000b). This training is successful in improving the likelihood for high-functioning ACL-injured athletes, or potential copers, to return to sport in the short-term without ligament reconstruction (Fitzgerald et al., 2000a, Hurd et al., 2008a). In non-copers, pre-operative perturbation training in combination with progressive quadriceps strengthening did not enhance their ability to return to sport when compared to strength training alone (Hartigan et al., 2010), but was effective in normalizing post-operative knee excursions during gait (Hartigan et al., 2009). In the U.S., prompt surgical intervention is typically advised for athletes with recurrent instability in an attempt to maximize return to sport abilities (Daniel and Fithian, 1994, Marx et al., 2003). In Norway, however, where delayed surgical intervention is the standard of care, researchers found that prolonged conservative management, including strength, agility, and other forms of neuromuscular training proved effective for 70% of non-copers (Moksnes et al., 2008). These investigations imply not only that a subgroup of non-copers exists, but that certain individuals may possess more adaptable neuromuscular systems than others.

ACL-injured females represent an interesting subgroup of non-copers for several reasons. Research has well established that women are at higher risk for ACL injury (Agel et al., 2005, Arendt and Dick, 1995), and more likely to be classified as non-copers than men (Hurd et al., 2008b). Post-operative outcomes also appear to be gender-specific. Following ACL reconstruction, women reported lower function on self-report scores (Ageberg et al., 2010) and demonstrated a reduced likelihood to return to sport (Ardern et al., 2011). There is growing evidence that there are functional differences between men and women following injury and surgery, yet no studies have sought to compare the gait mechanics of men and women after ACL injury or after therapeutic intervention. Neuromuscular training focused on speed, agility, power, and form effectively address the biomechanical behaviors known to predict injury risk (Hewett et al., 2006, Hewett et al., 1999). Perturbation training, specifically, has been shown to enhance the muscular behaviors of healthy female athletes (Hurd et al., 2006). While perturbation training has produced varied results in non-copers as a group, and appears to have little effect on healthy male athletes (Hurd et al, 2006), comparing the movement strategies of male and female non-copers may clarify the effects of this training. Ultimately, understanding gender-specific movement behaviors before and after neuromuscular training could have significant implications on the rehabilitation of non-copers. Therefore, the purpose of this investigation was to describe the acute effects of pre-

operative perturbation training on the movement behaviors of male and female non-copers. We hypothesized that prior to perturbation training women would demonstrate smaller peak angles, joint excursions and joint extensor moments in the involved knee when compared to their own uninjured limb and both limbs of men. We hypothesized female non-copers would demonstrate the characteristic non-coper compensatory hip strategy, including larger peak angles, joint excursions, and joint extensor moments at the involved hip compared to the uninjured limb and both limbs of male non-copers. Following perturbation training, it was hypothesized that only extensor moment asymmetries at the hip and knee would persist for both sexes.

Methods

Twenty-one ACL-deficient athletes (Table 1) were classified as non-copers within seven months of their index injury using an ACL-deficient functional screening examination (Fitzgerald et al., 2000a). All athletes participated in cutting, pivoting, or jumping activities for more than 50 hours/year prior to injury. Significant concomitant injuries (symptomatic meniscus tear, large osteochondral defects, or associated grade III ligament strains) excluded athletes from the potential subject pool. Clinical examination and magnetic resonance imaging (MRI) were used to determine the presence of associated injuries and confirm complete ACL rupture. Participants were selected for this study from a larger ongoing randomized controlled trial if their pre-operative physical therapy included progressive quadriceps strength training combined with perturbation training. Ten additional healthy subjects (age: 20.6 years (1.8); five males, five females) participating at the same level of activity as the ACL-deficient athletes, were recruited for this study in order to determine minimal clinically important differences (MCID) between limbs (Table 2). All testing procedures were approved by the Institutional Review Board.

Perturbation training involves the guided manipulation of movable support surfaces by a trained physical therapist to elicit specific muscular co-activation of the lower extremity (Figure 1). Progression of the ten sessions was criterion-based for each of the three training phases (early, middle, and late), and emphasized accurate and consistent muscular activity in response to manipulation of the boards (Fitzgerald et al., 2000c). The protocol began with double limb support to accommodate the patient to the three types of support surfaces, and progressed quickly to single limb standing. Proper patient positioning and knee alignment was addressed with cues by the physical therapist as needed throughout the training. Perturbations were administered with increasing speed and amplitude once the patient demonstrated effective and selective muscular responses at the slowest speeds and smallest amplitudes. Unexpected perturbations and distractions, and perturbations in combined planes of motion were integrated into the middle phase of treatment, while sports-specific tasks were the focus of the late phase (last three sessions) of perturbation training. Perturbation training and details of the criterion-based progression are described extensively elsewhere (Fitzgerald et al., 2000c, Fitzgerald et al., 2000b)

Biomechanical data of walking were collected before and after perturbation training. Kinematic data from both lower extremities were sampled at 120Hz with an 8-camera 3-dimensional motion capture system (VICON, Oxford Metrics Ltd, London, England). Passive retro-reflective markers were secured to the subjects' lower extremities and pelvis in order to identify joint centers and segment pose. Kinetic data were collected simultaneously at 1080Hz from a six-component force platform embedded in the laboratory's walkway (Bertec, Worthington, OH) and synched with kinematic data. Five walking trials at a controlled, self-selected speed were collected and analyzed for each limb. Gait speed was controlled between sessions (±5% for each subject). Trials were accepted if the subject did not intentionally target the force plate and made plate contact with only one foot at a time.

Rigid body analysis and inverse dynamics were performed using custom software programming (Visual3D, C-Motion, Inc, Germantown, MD; LabVIEW 8.2, National Instruments Corp, Austin, TX). Kinematic and kinetic data were lowpass filtered at 6Hz and 40Hz, respectively. Gait events (initial contact and end of stance) were identified using a 50N force plate threshold. Joint angles were calculated using rigid body analysis. Joint moments were calculated using inverse dynamics, then normalized to the subject's body mass (kg) multiplied by height (m). Walking trials were time normalized to 100% of stance and then averaged for statistical analyses.

All data were analyzed using SPSS (SPSS 17.0, Chicago, IL). Hip and knee kinematics and kinetics of men and women before and after training were evaluated using a repeated measures analysis of variance (ANOVA) with a between subjects factor of gender, within subjects factors of time and limb, and gait speed as a covariate. Variables of interest included hip and knee joint angles at initial contact and peak knee flexion, joint excursions during weight acceptance, and joint extensor moments at peak knee flexion. If significant interactions were found, paired t-tests were used to determine where limb differences existed. A priori significance level was set at 0.05. Effect sizes (ES) and minimal clinically important difference (MCID) values for joint kinematics and kinetics established from ten healthy active subjects (Table 2) were used to qualitatively compare the limb behaviors of men and women over time, and determine the presence of clinically meaningful asymmetry.

Results

Of the six kinematic variables analyzed, a significant time x limb x gender interaction was found only for hip excursion during weight acceptance ($P = 0.012$) (Figure 2). Prior to perturbation training, only female non-copers possessed significantly different hip joint excursions between limbs (Involved: 11.5° (4.7), Uninvolved: 6.9° (4.2), $P = 0.009$, ES: 1.03) (Figure 2). No additional time x limb interactions or main effects were found with regard to joint kinematics for our female and male non-copers.

While no statistically significant interactions were found for peak knee flexion angle, ($P = 0.073$) or peak hip flexion angle ($P = 0.069$) (Figure 3), only women showed clinically meaningful kinematic asymmetries between limbs prior to perturbation training (Table 3). Specifically, women demonstrated smaller involved limb peak knee flexion angles (Involved: 20.4° (6.1), Uninvolved: 26.4° (5.4), ES: 1.06) and hip flexion angles (Involved: 20.4° (7.6); Uninvolved: 24.4° (6.1), ES: 0.58). Prior to perturbation training, female non-copers also demonstrated smaller knee joint excursions in their involved limb (14.3° (5.8)) (Figure 3) when compared to that of their uninvolved limb (18.2° (5.7), ES = 0.68), and compared to both limbs of the male non-copers (ES ≥ 0.68). Following perturbation training, women demonstrated no clinically meaningful differences in knee flexion angles (Involved: 23.0° (4.9), Uninvolved: 24.9° (5.1), ES = 0.38), hip flexion angles (Involved: 21.3° (8.1), Uninvolved: 21.9° (6.6), ES = 0.08), knee excursions (Involved: 14.8° (5.8), Uninvolved: 16.8° (5.9), ES = 0.34), and hip excursions (Involved: 9.7° (3.8), Uninvolved: 7.9° (4.3), ES = 0.44) between limbs.

Comparatively, men did not demonstrate clinically meaningful asymmetries between limbs before perturbation training, on any of the kinematic variables. Following perturbation training, however, men demonstrated clinically meaningful differences in knee flexion angle between limbs (Involved: 24.8° (6.6), Uninvolved: 28.1° (5.1), ES = 0.56) (Table 3).

No significant time x limb x gender interactions were found for hip and knee joint kinetics ($P > 0.05$). Only a main effect of limb was found for internal hip extensor moments ($P = 0.011$) (Figure 4). Though no statistically significant interactions were found, clinically

meaningful asymmetries were identified between the limbs of both men and women (Table 3). Prior to perturbation training, the involved limbs of women demonstrated smaller hip (0.37Nm/kg*m (0.12), ES = 0.49) and knee (0.32Nm/kg*m (0.17), ES = 0.83) extensor moments at PKF when compared to their uninjured limbs (Hip: 0.44Nm/kg*m (0.16); Knee: 0.43Nm/kg*m (0.08)), and to both the injured and uninjured limbs of men. Men also demonstrated clinically meaningful differences in knee extensor moments between limbs prior to perturbation training (Involved: 0.38Nm/kg*m (0.15), Uninvolved: 0.46Nm/kg*m (0.18), ES = 0.48). Following perturbation training, women demonstrated no clinically meaningful difference in hip moments between limbs. Clinically meaningful differences in knee extensor moment between limbs persisted for both men (ES = 0.40) and women (ES = 0.69) following perturbation training.

Discussion

The aim of this work was to characterize the movement behaviors of male and female non-copers before and after perturbation training. We hypothesized that women, when compared to men early after injury, would present with unique and asymmetrical limb behaviors. It was also hypothesized that women's gait abnormalities would resolve following pre-operative perturbation training. As expected, a gender-specific response to injury and perturbation training emerged.

During the weight acceptance phase of gait, female non-copers demonstrated more asymmetrical limb behaviors early after injury than their male counterparts. Specifically, the involved limb of these women showed reduced hip and knee flexion angles and moments at peak knee flexion, truncated knee excursions, and increased hip excursions during weight acceptance when compared to their own uninvolved limb and the limbs of the male non-copers. In combination, reduced motion and moments at the knee have been identified as a stiffened knee strategy, which is representative of the gait behaviors of non-copers as previously described (Rudolph et al., 2001). Conversely, the pre-training gait behaviors of our male non-copers seem to reflect a superior neuromuscular response to injury, with the only meaningful asymmetry noted in knee extensor moments.

The response to perturbation training was different between our male and female non-copers as well. Following training, all but one of the women's gait asymmetries had resolved, suggesting perturbation training may be an effective pre-operative intervention to address aberrant gait strategies in female non-copers. Knee extensor moment asymmetries, however, persisted after training for both the men and women in our group of non-copers. The unremitting asymmetry in knee joint moments is characteristic of ACL-injured athletes even several months after ACL reconstruction (DeVita et al., 1998, Timoney et al., 1993), and therefore, is not unexpected in this cohort of poorer functioning and conservatively treated non-copers.

Female athletes have emerged as a cohort of significant interest within the ACL-injured population (Ageberg et al., 2010, Ardern et al., 2011, Hurd et al., 2008b, Shelbourne et al., 2009). Women are not only more likely to demonstrate poorer performance than men early after injury (Ageberg et al., 2010, Hurd et al., 2008b) but they also demonstrate poorer outcomes following surgery (Ageberg et al., 2010, Ardern et al., 2011). Other work has provided equivocal results on the outcomes between genders following ACL injury and surgery (Barber-Westin et al., 1997, Ott et al., 2003). These findings, however, may have underestimated actual differences since subject pools were not classified according to functional capacity after injury, and may therefore have been heterogeneous samples. A growing body of research proposes that identifying factors that influence functional classification of ACL-deficient individuals may positively influence clinical decision-

making and rehabilitation efforts (Eastlack et al., 1999, Fitzgerald et al., 2000a, Hurd et al., 2008a). Subsequent analysis, with larger samples, comparing the neuromuscular behaviors of male and female non-copers might further aid appropriate identification and prescription of therapeutic interventions.

Little is known about the recovery of normal gait mechanics in men and women following ACL injury or reconstruction. Healthy men and women demonstrate similar sagittal plane gait behaviors (Chumanov et al., 2008, Ferber et al., 2003, Hurd et al., 2004). Following ACL injury, our data indicate that men and women may have different movement adaptations and that their responsiveness to neuromuscular training injury might also be unique. Many studies have evaluated and subsequently documented the effectiveness of neuromuscular training in altering the movement strategies of uninjured females (Filipa et al., 2010, Hewett et al., 2006, Hurd et al., 2006, Paterno et al., 2004). Perturbation training, specifically, has been shown to be an effective neuromuscular training tool for healthy women (Hurd et al., 2006) and when implemented as a pre-operative paradigm for non-copers (Hartigan et al., 2009). This is the first study to observe the acute effects of perturbation training on non-copers, and more specifically that of male and female non-copers.

Though previously thought to be a homogeneous group, non-copers have demonstrated their ability to be adaptable athletes following injury (Hartigan et al., 2009, Moksnes et al., 2008). Hartigan and colleagues hypothesized that the addition of perturbation training to a progressive pre-operative quadriceps strengthening regimen for non-copers would improve the gait mechanics and functional outcomes more than quadriceps strength training alone (Hartigan et al., 2009, Hartigan et al., 2010). While there was a noted positive effect on knee excursions during gait in the individuals who received perturbation training (Hartigan et al., 2009), their sport performance was no better than the strength only group (Hartigan et al., 2010). These findings support the hypothesis that some non-copers possess more malleable neuromuscular systems than others. Additionally, the varied functional capacities of non-copers after ACL reconstruction implies that important subgroups exist within this cohort (Hartigan et al., 2010, Moksnes et al., 2008). The results of this work and the work of others (Ageberg et al., 2010, Ardern et al., 2011, Hurd et al., 2008b) point to gender, in particular, as a meaningful group of ACL-injured athletes, and a factor that should be considered in future investigations evaluating the outcomes of non-copers.

There are some limitations to this study. Our sample was limited to the men and women who received perturbation training as part of a larger randomized controlled trial. The men and women in this group of non-copers walked at different speeds, which was not the case for the men and women within the larger randomized trial. While our data analysis did not yield the statistically significant interactions as hypothesized, our limb comparisons using MCIDs and effect sizes indicate that clinically meaningful limb asymmetries following ACL injury may be more characteristic of female non-copers than males. Similarly, the responsiveness of female non-copers to perturbation training also suggests a unique and promising neuromuscular adaptability in this group. Lastly, it cannot be assumed that these gait adaptations are indicative of meaningful sports-related functional improvements, or warrant non-operative management for most non-copers. This study provides a preliminary, but novel step, towards determining whether men and women recover differently in the wake of ACL rupture. Long-term analysis of larger samples with concurrent clinical performance measures will allow for a better understanding of the recovery of ACL-deficient athletes.

Conclusion

Differences in the gait characteristics of male and female non-copers have not been previously described. Our female non-copers not only presented with poorer performance following injury, but also seem to possess the abnormal gait behavior that is characteristic of non-copers as previously described. These data suggest that women may benefit the most from pre-operative perturbation training, as evidenced by the adoption of more symmetrical movement patterns. Our findings also underscore that non-copers are a variable group, and more specifically, that gender appears to be a meaningful subgroup in this population. A differential response to ACL reconstruction and post-operative rehabilitation may also exist. Therefore, future investigations into the gait characteristics and functional outcomes of athletes following ACL injury should consider the effects of gender.

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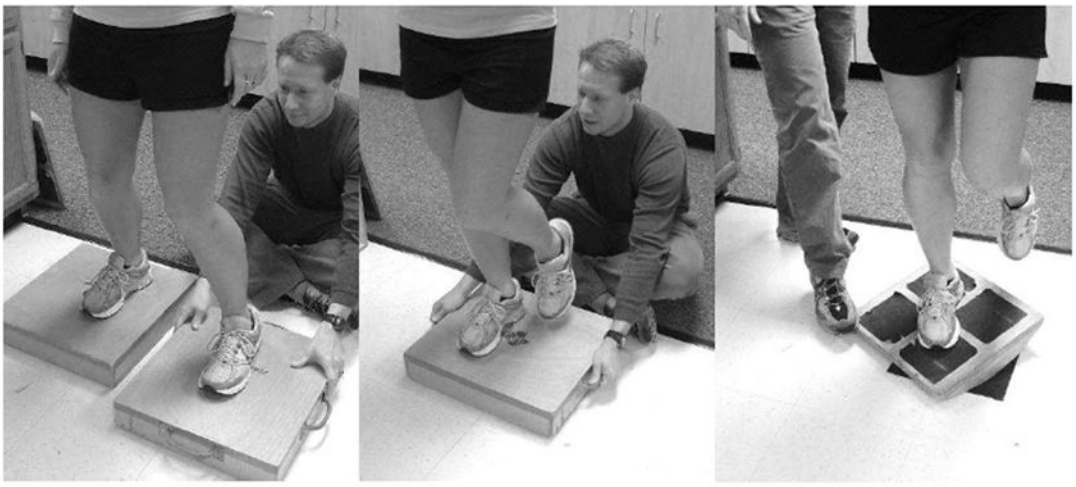

Figure 1.
Three different board configurations during perturbation training. From left to right: rollerboard and stationary platform combination, single rollerboard, and rockerboard.

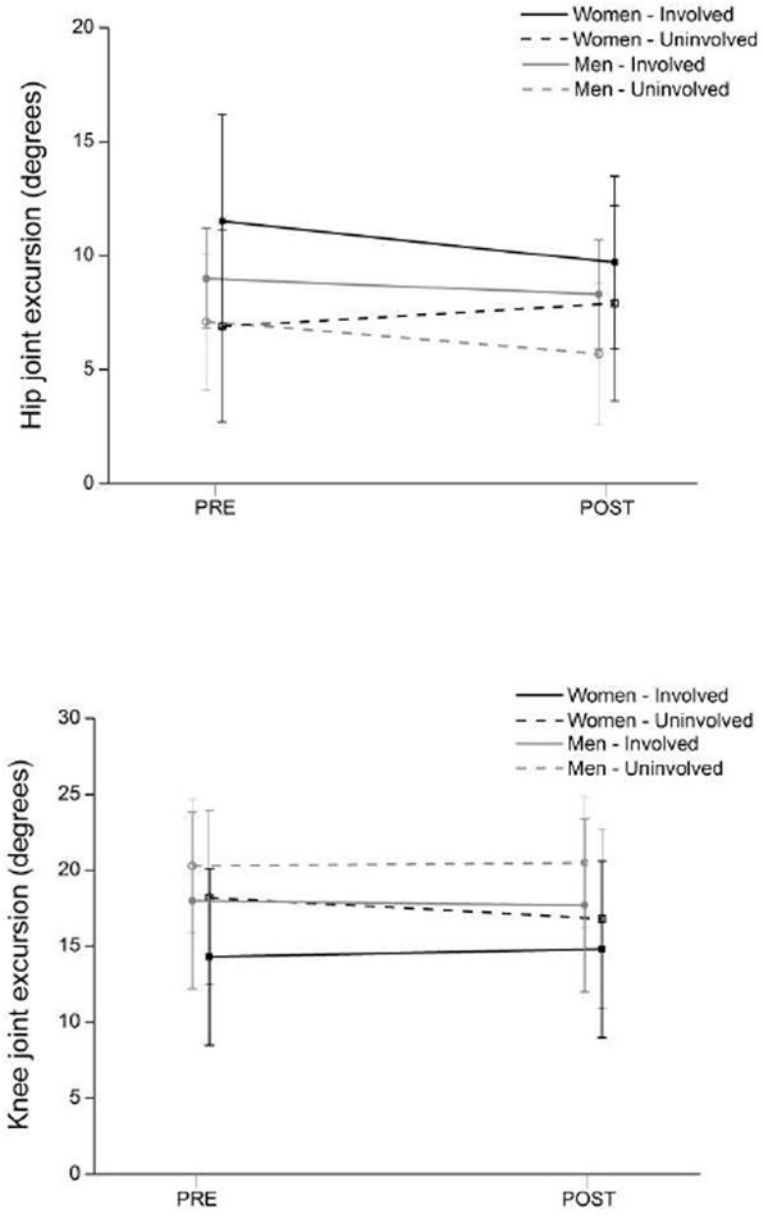

Figure 2.
Mean sagittal plane hip and knee excursions of men and women at PKF, before (PRE) and after (POST) perturbation training. Bars = standard deviations.

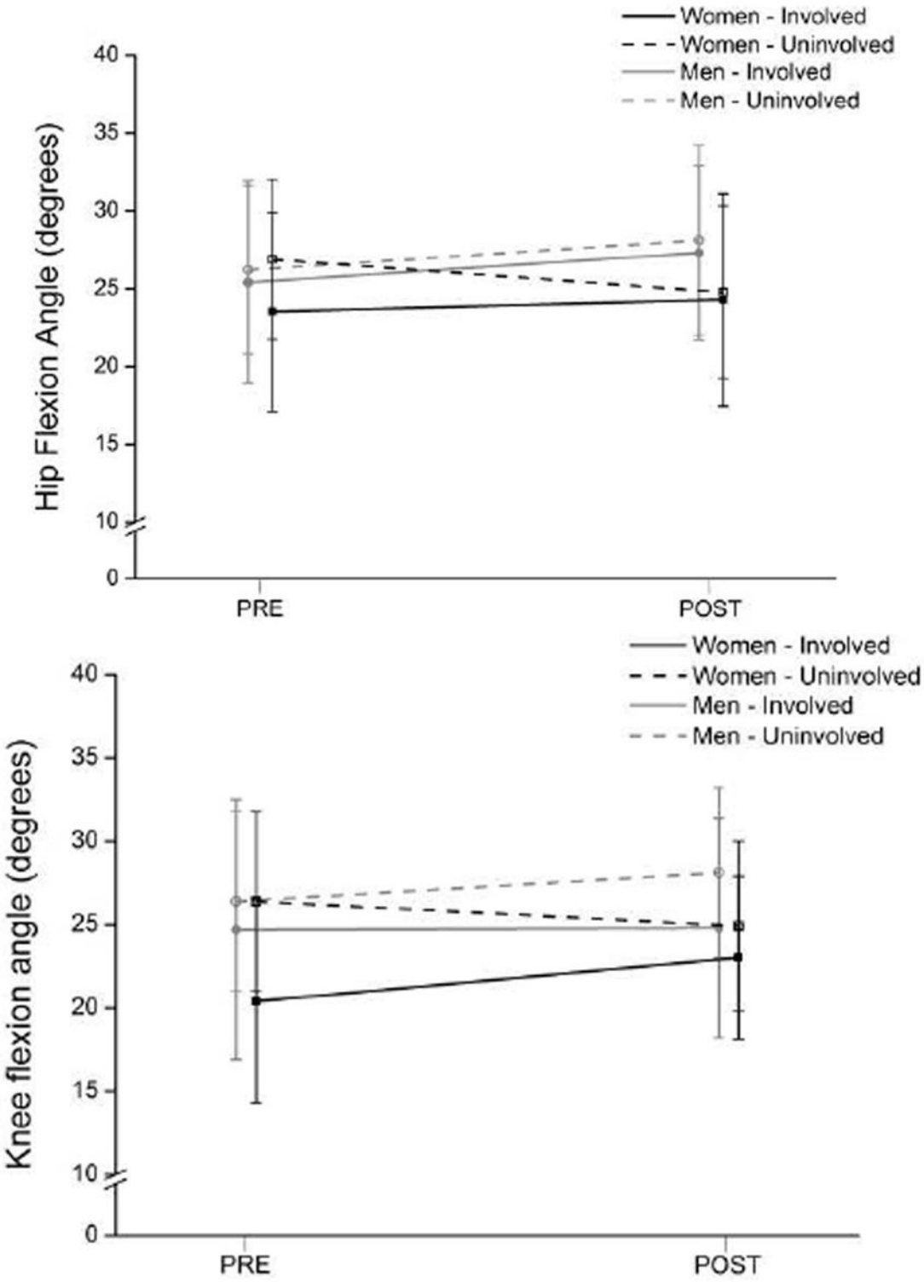

Figure 3.
Mean sagittal plane hip and knee angles of men and women at PKF, before (PRE) and after (POST) perturbation training. Bars = standard deviations.

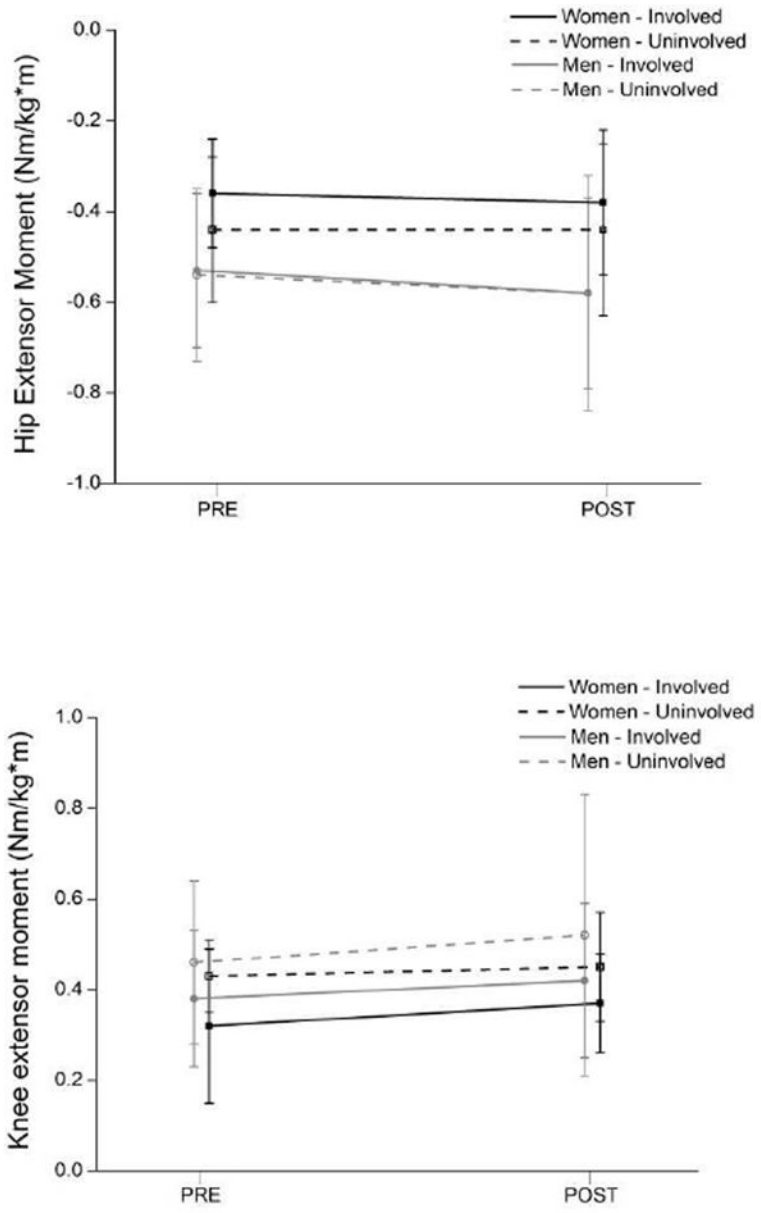

Figure 4.
Mean hip and knee extensor moments of men and women at PKF, before (PRE) and after (POST) perturbation training. Bars = standard deviations.

Table 1

Participant demographics

NON-COPERS	Men (n=12)	Women (n=9)	p-value
Age (years)	25.0 (8.7)	33.7 (12.6)	0.08
BMI (kg/m^2)	30.5 (5.1)	28.4 (7.2)	0.43
Time of injury to screen (wks)	13.1 (9.3)	7.4 (5.7)	0.12
Training (wks)	3.5 (1.7)	3.5 (1.9)	0.96
Walking velocity (m/s)	1.58 (0.12)	1.46 (0.14)	0.047*

* $p \leq 0.05$ is significant

Table 2

Minimal clinically important difference (MCID) values for sagittal plane hip and knee kinematics and kinetics.

Gait variable	MCID
Knee kinematics during weight acceptance	3°
Hip kinematics during weight acceptance	3°
Knee moment at peak knee flexion	0.04 Nm/kg*m
Hip moment at peak knee flexion	0.06 Nm/kg*m

Table 3

Limb asymmetry of men and women before (Pre) and after (Post) perturbation training. Minimal clinically important differences (MCIDs) between limbs are denoted with a check (√).

	WOMEN		MEN	
	Pre	**Post**	**Pre**	**Post**
Knee flexion angle at PKF	√			√
Knee flexion excursion at PKF	√			
Knee extensor moment at PKF	√	√	√	√
Hip Flexion Angle at PKF	√			
Hip Flexion Excursion at PKF	√			
Hip Extensor Moment at PKF	√			