GENDER DIFFERENCES IN KNEE STABILITY IN RESPONSE TO WHOLE-BODY VIBRATION

BORJA SAÑUDO,[1] ADRIAN FERIA,[1] LUIS CARRASCO,[1] MOISÉS DE HOYO,[1] RUI SANTOS,[2,3] AND HUGO GAMBOA[2,3]

[1]Department of Physical Education and Sport, University of Seville, Seville, Spain; [2]Plux Wireless Biosignals, Lisbon, Portugal; and [3]Department of Physics, The New University of Lisbon, Lisbon, Portugal

ABSTRACT

Sañudo, B, Feria, A, Carrasco, L, de Hoyo, M, Santos, R, and Gamboa, H. Gender differences in knee stability in response to whole-body vibration. *J Strength Cond Res* 26(8): 2156–2165, 2012—The purpose of this study was to determine whether there are kinematic and electromyographic (EMG) differences between men and women in how the knee is controlled during a single-legged drop landing in response to whole-body vibration (WBV). Forty-five healthy volunteers, 30 men (age 22 ± 3 years; weight 76.8 ± 8.8 kg; height 179.0 ± 6.8 cm) and 15 women (age 22 ± 3 years; weight 61.0 ± 7.7 kg; height 161.9 ± 7.2 cm) were recruited for this study. Knee angles, vertical ground reaction forces, and the time to stabilize the knee were assessed after single-legged drop landings from a 30-cm platform. Surface EMG data in rectus femoris (RF) and hamstrings (H) and knee and ankle accelerometry signals were also acquired. The participants performed 3 pretest landings, followed by a 3-minute recovery and then completed 1 minute of WBV (30 Hz to 4 mm). Before vibration, the female subjects had a significantly higher peak vertical force value, knee flexion angles, and greater H preactivity (EMG_{RMS} 50 milliseconds before activation) than did the male subjects. In addition, although not significant, the medial-lateral (ML) acceleration in both knee and ankle was also higher in women. After WBV, no significant differences were found for any of the other variables. However, there was a decrease in the RF to H activation ratio during the precontact phase and an increase in the ratio during the postcontact phase just in women, which leads to a decrement in ML acceleration. The gender differences reported in knee stability in response to WBV underline the necessity to perform specific neuromuscular training programs based on WBV together with instruction of the proper technique, which can assist the clinician in the knee injury prevention.

KEY WORDS injury prevention, neuromuscular control, vibration training, lower-limb, kinematics

INTRODUCTION

A large body of literature suggests that women demonstrate a substantially greater risk, approximately fourfold to eightfold higher, to suffering acute injury of the anterior cruciate ligament (ACL) compared with men (13,20). Most of these injuries occur in noncontact situations such as landing activities because of the rapid changes in the forces applied to the knee joint (3,16). Therefore, identification of risk factors that predispose female athletes for ACL injury has a high clinical relevance.

The potential underlying mechanism to these differences between genders has been categorized in anatomical, hormonal, and biomechanical or neuromuscular imbalances (18), but there is clear consensus that sex differences in neuromuscular and biomechanical function may be the most compelling factors to explain the different rates of injury in men and women. It has been suggested that the absence of dynamic knee joint stability or neuromuscular control of the lower extremity in female athletes contributes to an increased knee injury rate (16). In addition, gender-specific muscle activation patterns and lower limb kinematics and kinetics have been documented (20). Differences in muscle activation have been reported in some studies supporting a tendency to higher activation of quadriceps and lower activation of hamstrings (H) in women compared with that in men; thus, women show quadriceps to hamstrings deficits and have delayed H reactions in response to anterior stress on the ACL (7,11,17,20,43,46,49). Several electromyographic (EMG) studies have evaluated gender differences and also indicate that female athletes display different neuromuscular responses, including timing (33) and magnitude (49) of muscle activation in situations where ACL injuries occur (2). This situation has also been related to the lower muscle stiffness produced by women in comparison with that produced by men (49).

Although there has been considerable interest in determining whether men and women differ in muscular activation,

---

Address correspondence to Borja Sañudo, bsancor@us.es.

26(8)/2156–2165

Journal of Strength and Conditioning Research

timing, recruitment patterns, musculotendinous stiffness, or a combination of these factors, to provide a potential explanation for the disparity in ACL injury rates, more research in needed to contribute to the understanding of the potential prevention mechanism. It is widely accepted that efficient neuromuscular control is essential to dynamic joint stability, and recent data support that neuromuscular training should be used in female athletes to decrease the incidence of ACL injuries (4). However, a better understanding of how exercises affect knee stability is of importance in enhancing injury prevention.

To date, injury-prevention programs have successfully incorporated unilateral landings (20) and strengthening in their protocols (15) because muscle contraction can decrease the incidence of injury to the knee. Other studies have investigated the effect of exercise on tibial translation (26), which may play an important role in stabilizing the knee (31) and there is some evidence of the use of neuromuscular electrical stimulation to restore and improve quadriceps function (23). However, there are contradictory results about the effects of training methods on the knee joint stabilization (26). More research is needed to determine the efficacy of various proprioceptive feedback mechanisms and the ultimate capacity of neuromuscular responses to stiffen the joint and protect the ACL under sudden loading conditions (42). In this sense, and considering that neuromuscular factors that contribute to knee stability include active muscle stiffness (38), muscle coactivity (21), and reflexive muscular activation (10), whole-body vibration (WBV), which is a new kind of somatosensory stimulus for proprioception has been shown to affect all these variables (6).

The WBV increases muscle strength (27) and improves neuromuscular performance based on an increase in the synchronization activity of the motor units (6), which might have an important role in neuromuscular control of the knee joint (31). However, there is a lack of scientific support about the effects of WBV on knee proprioceptors. Only, Moezy et al. (32) compared the effects of WBV training and conventional therapy on knee proprioception and postural stability in ACL reconstructed subjects. The authors reported improved proprioception and balance after WBV but a greater improvement of postural stability in the WBV group in comparison with conventional training.

It was suggested that vibration stimulates the skin receptors, muscle spindles, joint mechanoreceptors, and changes in the vestibular system (6). It seems that during a WBV loading, skeletal muscles undergo small changes in muscle length, including the activation of muscle spindles, mediation of the neural signals by afferent channels, and activation of muscle fibers via large alpha-motor neurons and may contribute to joint stability by modulating muscle stiffness via reflex action on gamma-motoneurons (44). This might cause an increase in the recruitment of the motor units through the activation of muscle spindles and therefore a more efficient use of the positive proprioceptive feedback, which was suggested to result in increased muscle strength because of neural adaptation (45).

One may argue that WBV affects the reflex activity of the muscles, which act as synergists to the ACL and thus the neuromuscular control of the knee joint. However, to the best of our knowledge, no study has investigated the effects of WBV training on knee proprioception before. Just one study aimed to investigate the effect of a single WBV exposure on the reflex activity of the H and on functional knee stability (31). The authors suggested that a single session of WBV results in a decrease in anterior tibial translation, which may play an important role in stabilizing the knee. No studies have investigated the differences between men and women when controlling the knee during a single-legged drop landing after the exposure to WBV. Therefore, the purpose of this study was to determine whether gender differences existed in muscle activity and knee kinematics in healthy people when performing a landing maneuver after the exposure to WBV. We hypothesized that the exposure to WBV would result in (a) differences in lower limb kinematics. Women would exhibit decreased vertical ground reaction forces (GRFs) compared with men, (b) decreased knee flexion angle during a single leg–landing task in both genders, and (c) differences in muscle activation timing. Concurrently, we presumed that vibration would result in the increased activation of the H, mainly in women (with a tendency to lower activation of H) and that knee joint control would be increased (d), an increase of muscle reflex activity that may in turn affect neuromuscular knee stabilization in both genders. We also hypothesized that some characteristic differences exist between the lower limb kinetics (knee and ankle acceleration) of male and female participants.

METHODS

Experimental Approach to the Problem

There are gender differences in neuromuscular and biomechanical functions, which may explain the different rates of injury in men and women. The different activation strategies or kinematics patterns contribute to an increased knee injury rate in women, which may also be because of the lower muscle stiffness produced by women. It is widely accepted that neuromuscular control, joint stiffness, or the efficacy proprioceptive feedback mechanisms can improve joint stability and decrease the incidence of ACL injuries. The WBV has been reported to improve all these mechanisms although no study has investigated neither the effects of WBV training on knee proprioception before nor the differences between men and women when controlling the knee while landing after the exposure to WBV. To observe the differences in the muscle activity and knee kinematics between men and women before and after the exposure to WBV, 45 healthy individuals performed 3 pretest single-leg drop landings from 30 cm, and after 3-minute recovery, they completed 1 minute of WBV (30 Hz to 4 mm) before a new landing. In all attempts, knee angles, vertical ground reaction forces, and the time to stabilize the knee were assessed. Surface EMG data in rectus femoris (RF) and H and knee and ankle accelerometry signals were also acquired. All outcomes were compared before and after WBV using a repeated-measures 2-way ANOVA (group × measurement time). The results of this study would potentially provide an additional insight into the mechanisms of ACL injury and would provide information for the development of injury-prevention programs that differentiate specific responses to WBV for both genders.

Subjects

Eighty-one subjects from the student population at the University of Seville were invited by mail and by word of mouth to participate in the study. Fifty subjects volunteered to participate. Medical histories were reviewed by a physician to assess the suitability for the study and exclusion criteria included the presence of lower extremity injury within 6 months before data collection. Five subjects did not fulfill the inclusion criteria (1 man had severe chondromalacia, 1 man and 1 woman meniscal tears, and 1 man and 1 woman a grade 2 or greater ligament injury) and were excluded from the study. The subjects with a history of minor strains, sprains, or chronic conditions such as tendinitis or bursitis in the dominant extremity that had completely healed or were causing no pain at the time could be included in the study. Forty-five healthy individuals, 30 men (age 22 ± 3 years; weight 76.8 ± 8.8 kg; height 179.0 ± 6.8 cm) and 15 women (age 22 ± 3 years; weight 61.0 ± 7.7 kg; height 161.9 ± 7.2 cm) participated in this study. To verify that sport experience and training history were similar between the sexes, data on sport activity and training history were collected on each subject, including running, practice, and weightlifting activities of the previous month. The participants had to be physically active, participating in a minimum of 20 minutes of physical activity 3 times per week. All the subjects played in intramural sports leagues at the university but had not participated in regular resistance or jump-training programs during the last 12 months. All the subjects had a very similar training volume (minimum 3 per week and maximum 4 per week), broken up into 1-hour sessions. The participants were asked to not perform heavy exercise during the 48 hours before the test. Each subject was informed of all the procedures, potential risks, and benefits associated with the study and was free to withdraw from the study at any time. All the experimental procedures were performed in accordance with the Helsinki Declaration, and the subjects were provided both verbal and written consent before participating. The procedures were approved by the institutional Human Research Ethics Committee.

Procedures

All the subjects were familiarized with the test procedures during the pretest orientation session. They were instructed on, and provided with a demonstration of, the correct performance of the jump exercise to be assessed during the test session. All the tests were preceded by a 5-minute warm-up consisting of cycling on a cycloergometer (Ergoline 900®, Ergometrics, Bitz, Germany) at 60 W (60 rpm), and the warm-up was followed by five 30-cm single-legged drop landings until they demonstrated the correct technique.

The participants performed the first single-leg drop landing onto a squared zone (50 × 40 cm) delimited into the force plate. After 1-minute recovery, this action was repeated twice (again with 1-minute recovery between trials). After a 3-minute recovery, the participants were placed on the vibrating platform and completed 1 bout of 1 minute (30 Hz to 4 mm). Immediately after the vibration was applied, the participants performed the single-leg drop landing again. All research was conducted during a period (between February and March) in which the participants were competing in their respective intramural leagues. In addition, all the testing procedures were performed during the same period (between 10:00 and 12:00 AM) in a room at an ambient temperature 22–24° C. All the subjects had a typical Spanish breakfast, and water intake was ad libitum.

Electromyography

The EMG signals of the dominant leg were collected. In accordance with the guidelines of SENIAM Project (19), self-adhesive bipolar surface electrodes (diameter: 1.5 cm, interelectrode distance: 3 cm; Blue Sensor®, Medicotest A/S, Olstykke, Denmark) were placed at 50% on the line from the anterior superior iliac spine to the superior part of the patella, to record the RF signal and for recording H parallel to the muscle approximately half the distance from the gluteal fold to the back of the knee (semitendinosus/semimembranosus muscles). The reference electrode was placed over the patella. Signals were acquired using a wireless system (bioPLUX, Lisbon, Portugal).

The EMG signals were first processed removing the *y* axis offset, by subtracting its mean value. A band-stop filter of 2 Hz centered on 50 Hz was applied, and the signals were then rectified and normalized to the respective maximum value. After applying a smoothing filter with a moving average window of 400 points, the EMG activation areas were determined as those were the resultant signal that had an amplitude >0.1. For both RF and H EMG signals, the neuromuscular preactivity (pre150 and pre50), which refers to the EMG 150 and 50 milliseconds before toe-down and the postactivation periods (pos150 and pos50), first 150 and 50 milliseconds after to toe-down were defined. In each landing, the EMG signal root mean square (EMG_{RMS}) in each period were computed, and after obtaining the frequency spectra signals by applying the Fast Fourier Transform algorithm, the respective mean frequency values were also calculated. A quadriceps-to-hamstring (RF/H) preactivity ratio was calculated by dividing the RF activity by the H activity.

Accelerometry

A triaxial accelerometer (xyzPLUX®; PLUX–Wireless Biosignals, Lisbon, Portugal) was used to measure accelerations onto the participant's ankle and knee. The sensors were set to measure accelerations within ±3*g* range. Accelerometers were stuck onto the skin at the tibial condyle level and at the peroneal malleolus level. Acceleration signals provided information related to participant's knee and ankle oscillations. The signals were preprocessed to exclude the influence of gravity. To consider only vibration-induced muscle displacements, the signals provided by the accelerometer were low-pass filtered by an application of a smoothing filter with a moving average window of 10 points. Accelerations in the medial-lateral (ML) and anteroposterior (AP) axis 60 milliseconds after to the toe-down were considered for both the knee and the ankle. For each time point, the signals were rectified, and then the mean values were computed.

Drop Landings

The participants performed 3 single-legged drop landings from a 30-cm platform onto a force plate (MuscleLab; Ergotest, Langesund, Norway) set at a sampling rate of 600 Hz and were used to measure the GRFs, to indicate time phases of initial ground contact (PF1) and maximum vertical GRF (PF2) acting as key reference points for kinematic analyses and also to determine the time to stabilize the knee, defined as the eccentric contact time (seconds). The peak GRF during landing was defined as the highest value attained from the force-time record for the landing phase (11). The GRF data were normalized by each participant's body mass. The participants wore no shoes to avoid its possible influence on the landing phase and were required to cross their arms over their chest and begin each trial in single-limb stance on the dominant leg. They then dropped off the platform and landed on the force plate using the same leg. Data were sampled and processed using a dedicated PC system (MuscleLab; Ergotest, Langesund, Norway).

Whole-Body Vibration

All the participants were familiarized with the vibrating platform (Power Plate®, North America Inc., Northbrook, IL, USA) and the proper positioning. During the test, the subjects should hold the half squat position on the platform (with a 100° knee flexion controlled by electronic goniometer). The WBV stimulus was induced at the plantar surfaces of the feet at a frequency of 30 Hz with a peak-to-peak displacement of 4 mm, which is considered the optimal combination to get the greater muscle performance (9).

Joint Kinetics

Three reflective markers were placed over the lateral malleolus, lateral condyle, and greater trochanter. The two-dimensional sagittal-plane-projection angle of knee was measured during all the tasks. A digital video camera was placed at the height of the subject's knee, 2 m beside the subject's landing target and aligned perpendicularly to the sagittal plane. The digital images were imported into a digitizing software program (Quintic 4®, Quintic Consultancy Ltd., Cambridge, United Kingdom). The knee flexion angle at touchdown and the knee flexion angle when the maximal GRF was reached were determined.

Statistical Analyses

The data represent means and the *SD*s. Possible statistical differences were analyzed using a repeated-measures 2-way ANOVA (group × measurement time). One-way analysis of variance (ANOVA) tests were used to analyze the difference between male and female subjects in all kinematics variables. Mean EMG data for the participants were analyzed for the differences between the 2 groups by using a multivariate ANOVA and then by using a 1-way ANOVA for results for each individual muscle. The level of significance was set at $p \leq 0.05$. All statistical analyses were performed using the SPSS, 15.0 (SPSS, Inc., Chicago, IL, USA) statistical software package.

RESULTS

Table 1 shows the results of the kinetic variables during the landing phase before and after WBV. Gender differences in both the knee flexion angle at touchdown ($p = 0.02$) and the

TABLE 1. Vertical ground reaction forces and kinematic data during 30-cm single-legged drop landings before and after WBV.*†

	Pretest			Postest		
Measures	Men	Women	*p*	Men	Women	*p*
PF1 (BW)	2.70 (1.12)	2.69 (0.96)	0.960	2.72 (0.91)	2.96 (1.05)	0.454
PF2 (BW)	6.44 (1.50)	8.49 (2.58)	0.002‡	6.73 (1.87)	7.99 (2.22)	0.065
T_stab (s)	1.92 (0.53)	2.04 (0.64)	0.548	1.76 (0.53)	1.57 (0.34)	0.214
Angle 1 (°)	142.41 (9.93)	151.00 (12.22)	0.021‡	147.96 (8.38)	147.00 (5.99)	0.711
Angle 2 (°)	124.07 (8.97)	130.15 (6.52)	0.034‡	124.79 (8.61)	128.23 (6.36)	0.205

*WBV = whole-body vibration; PF1 = first peak vertical force value; PF2 = second peak vertical force value; BW = times body weight; T_stab = time to stabilize the knee; angle 1 = knee flexion angle in touchdown; angle 2 = knee flexion angle when the maximal vertical ground reaction force was reached.

†Data are reported as mean (*SD*).

‡$p < 0.05$ (p values are for intergroup differences).

TABLE 2. Electromyographic activity during 30-cm single-legged drop landings before and after WBV.*†

	Pretest			Postest		
Measures	Men	Women	*p*	Men	Women	*p*
RMS_pre50_RF	0.06 (0.35)	0.07 (0.35)	0.266	0.05 (0.03)	0.05 (0.02)	0.658
Freq_pre50_RF	131.98 (20.23)	128.02 (19.29)	0.558	138.06 (16.60)	127.71 (17.87)	0.076
RMS_pos50_RF	0.09 (0.02)	0.09 (0.02)	0.477	0.10 (0.03)	0.09 (0.02)	0.854
Freq_pos50_RF	128.23 (16.39)	121.04 (23.50)	0.263	123.95 (15.97)	126.15 (22.28)	0.719
RMS_pre50_H	0.08 (0.04)	0.12 (0.06)	0.048‡	0.10 (0.05)	0.08 (0.05)	0.239
Freq_pre50_H	161.13 (14.93)	157.67 (6.09)	0.428	153.81 (11.64)	155.44 (14.64)	0.701
RMS_pos50_H	0.11 (0.04)	0.11 (0.04)	0.746	0.11 (0.05)	0.09 (0.03)	0.329
Freq_pos50_H	146.72 (25.29)	136.41 (44.02)	0.826	143.98 (17.01)	130.81 (44.69)	0.171
Ratio RF/H_preRMS	0.77 (0.51)	0.82 (0.92)	0.794	0.73 (0.69)	.071 (0.25)	0.954
Ratio RF/H_preFreq	0.82 (0.14)	0.81 (0.13)	0.801	0.90 (0.13)	0.83 (0.15)	0.111
Ratio RF/H_posRMS	0.98 (0.52)	0.98 (0.58)	0.998	1.01 (0.49)	1.08 (0.36)	0.651
Ratio RF/H_posFreq	0.90 (0.20)	0.82 (0.21)	0.280	0.88 (0.18)	0.89 (0.18)	0.866

*WBV = whole body vibration; RMS_pre50 = preactivation (50 milliseconds before ground contact); Freq_pre50 = preactivation frequency values; RMS_pos50 = postactivation (50 milliseconds after the end of activation); Freq_pos50 = postactivation frequency values; ratio RF/H = RF to H activation ratios during the precontact and postcontact phases; RF = rectus femoris; H = hamstrings.

†Data are reported as mean (*SD*).

‡$p < 0.05$ (p values are for intergroup differences).

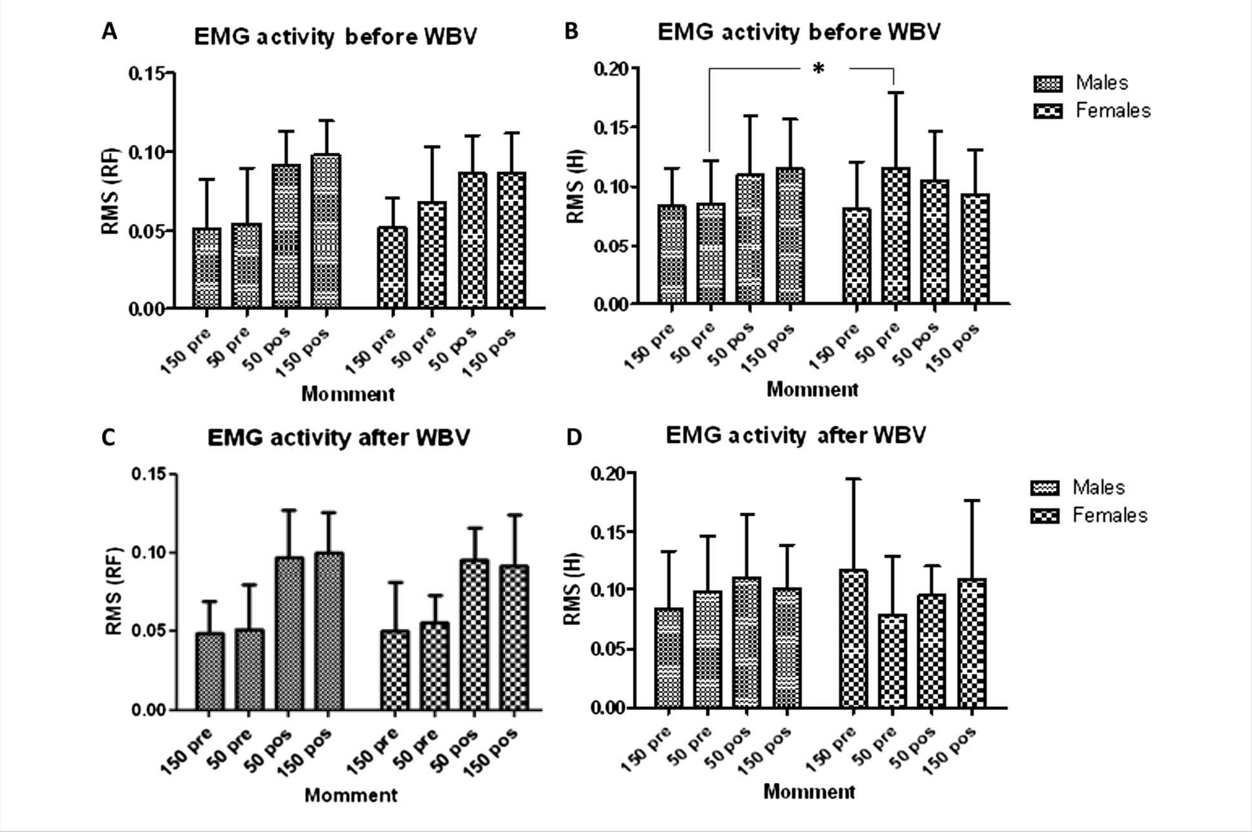

Figure 1. Comparison of EMG_{RMS} in RF (A) and H (B) during the first 150 and 50 milliseconds before ground contact and during the subsequent 50 and 150 milliseconds between men and women before and after whole-body vibration (C, D). Mean values (*SD*) are displayed. *Significant differences between genders. EMG = electromyography; RMS = root mean square; RF = rectus femoris; H = hamstrings.

Table 3. Acceleration data during 30-cm single-legged drop landings before and after WBV.*†‡§

Measures	Pretest			Postest		
	Men	Women	*p*	Men	Women	*p*
AP_knee (g)	1.66 (0.43)	1.46 (0.40)	0.160	1.76 (0.36)	1.54 (0.45)	0.095
ML_knee (g)	1.42 (0.40)	1.65 (0.50)	0.122	1.41 (0.44)	1.49 (0.49)	0.604
AP_ankle (g)	2.32 (0.39)	2.29 (0.32)	0.765	2.29 (0.41)	2.36 (0.45)	0.623
ML_ankle (g)	0.86 (0.32)	1.00 (0.19)	0.147	0.89 (0.27)	0.91 (0.27)	0.839

*WBV = whole-body vibration; AP = anteroposterior axis; ML = medial-lateral axis.

†Data are reported as mean (*SD*).

‡Acceleration 60 milliseconds after the ground contact with or without WBV in both the knee and ankle.

§*p* Values are for intergroup differences.

knee flexion angle when the maximal GRF was reached ($p = 0.03$) during the postcontact phase of the jump were found in the pretest. In addition, during this phase, women demonstrated greater PF2 ($p = 0.02$) compared with that of the men. After WBV, no significant differences were found for the GRF or the knee flexion angles. However, there was a trend toward a different PF2 ($p = 0.06$). Thus, a decrement of 6% was found in women, whereas men even experienced an increment (4%). The time to stabilize the knee was significantly lower in both men and women ($p < 0.05$) after WBV, although no gender differences were found.

The magnitude of the EMG activation and the activation ratios in RF and H are reported in Table 2. During the pretest, no gender differences in the magnitude of muscle activation during the precontact phase of the jump were found for RF. Significant differences in EMG_{RMS} activity was shown in H 50 milliseconds before activation in women compared with that in men. During the postcontact phase of the jump, men demonstrated greater RF activation ($p = 0.26$) compared with that in women. When the EMG activity was assessed after WBV, no significant differences were found. In the precontact phase of the jump, men showed a trend toward a greater EMG frequency of the RF ($p = 0.076$) than did women and although none was significant, the EMG_{RMS} of the H decreased in women after WBV (27%; $p = 0.475$). On the other hand, during the postcontact phase, the activation of RF increased in women (4%; $p = 0.687$), whereas a decrement in the H activation was experienced (4%; $p = 0.999$)

Timing of activation statistical analysis in RF and H (Figure 1) revealed that in the precontact phase of the jump, 150 milliseconds before the activation both men and women showed a similar response. However, 50 milliseconds before the activation, women showed a greater EMG_{RMS} in both RF and H (Figure 1A, B). After WBV, no significant differences were found for the muscles assessed during the precontact and postcontact phases of the jump (Figure 1C, D). Although a greater activation of the H was found in women 150 milliseconds before the ground contact.

The RF to H activation ratios (RMS and frequency) during the precontact and postcontact phases of the drop landing before and after WBV between men and women are also shown in Table 2. No significant differences were found for the activation ratios when the activation of the RF and H are averaged and expressed as a ratio. In the pretest, during the postcontact phase of the jump, men demonstrated a higher RF/H activation ratio than women ($p = 0.280$) did. When the analysis was performed after WBV, men increased the activation 50 milliseconds before the ground contact, whereas women showed a greater activation in the postcontact phase. In none of the cases were significant differences were found.

Finally, the acceleration of the knee and ankle during the drop landings before and after WBV is shown in Table 3. No significant differences were found during the precontact or postcontact phase either before or after WBV. However, in the pretest, men displayed a greater AP knee acceleration (12%; $p = 0.160$) and a lower ML knee acceleration (14%; $p = 0.122$) than women did. Regarding the ankle, women showed again a greater ML acceleration (14%; $p = 0.147$). After WBV, women experienced a decrement in the knee (10%; $p = 0.963$) and ankle (9%; $p = 0.997$) ML acceleration.

DISCUSSION

The purpose of this study was to observe the differences in the muscle activity and knee kinematics during 30-cm single-legged drop landings between men and women before and after the exposure to WBV. The specific aim of this research was to evaluate the gender differences in knee stability in response to WBV, which had not been previously addressed. The main finding of this study is that although women displayed a significantly greater GRF and H activity before the ground contact, an acute bout of WBV might reduce GRF and H activity in women, increasing cocontraction. On the other hand, no gender differences in neuromuscular activity of the quadriceps were observed after WBV. Finally, WBV decreases women ML acceleration in both the knee and ankle.

Biomechanical and neuromuscular imbalances were reported to explain the different rates of knee injury in men and women. In this sense, the results of the examination of gender differences during single-legged drop landings presented in this study confirmed previous research findings that women land with increased GRF (22). Considering that PF2 was previously matched with the moment when ACL resists the largest strain during the landing (37), the results of this study indicate that women may be at a greater risk of injury. However, PF2 decreased in this population group after WBV, which was reported to reduce the risk of injury during the landing movement (1). In addition, women landed with a greater knee extension, which has also been cited as a predisposing factor to knee injury (36). Markolf et al. (28) reported that quadriceps forces can produce anterior tibial translation and increase in ACL mainly when the knee is flexed $\leq 40°$. In this study, both men (38°) and women (29°) displayed lower degrees. It seems that the neuromuscular system may attempt to prevent falls during unilateral landings by limiting excessive knee flexion (3), and this may also be the reason why after WBV there was a light decrement in the knee flexion angle at touchdown. This is consistent with the results reported by Gehring et al. (14) indicating that a simultaneous activation of all the aspects of the quadriceps muscle may likely lead to a better control of the frontal plane motion in the knee joint.

Another important finding in this study was related to the neuromuscular control of the lower extremity, which may be related to the incidence of ACL injuries (4). There is evidence in the literature reporting gender-specific muscle activation strategies and differences in timing or even the muscle stiffness (33,49).

Differences between men and women in muscular activation during jumping activities have been reported in the literature. Although most studies support a tendency to higher activation of quadriceps and lower activation of H or even higher EMG activity means (50) in women compared with that in men, others did not report preactivity patterns for the RF or H muscles (7,43,46). Our results neither showed differences in the preactivation phase, which is consistent with the findings of Cowan and Crossley (8) who demonstrated that there were no differences in the onset of EMG or peak activity of the thigh and leg muscles between genders.

In this study, women showed greater activation of the H than men did during the precontact phase of the jump, which contrasts with the results of Bencke and Zebis (2) who found lower H activation during 50 milliseconds before initial ground contact, indicating lower H force in the first part of ground contact for the female subjects. Most research examining this issue has failed to find significant gender differences in H activation upon landing during functional movements (7,30,35). Although Sell et al. (40) also found a greater H activation in women, which suggests that women may be H dominant. This situation was reported to reduced the ACL load because H is synergistic to the ACL. However, because women relied more on their H, the initial increased use of these muscles in comparison with the use of RF muscles could place greater stress on the ACL in these female athletes (2). A greater H preactivity was found 150 milliseconds before the activation in women, but this response was just seen in men 50 milliseconds before the activation. These findings were partially explained by Melnyk et al. (31) suggesting that a short bout of WBV causes an increase in the short latency responses activity of the H and does not influence the medium latency responses activity of the H. In addition, Krosshaug et al. (24) showed that the timing of noncontact ACL injury ranges from 17 to 50 milliseconds after initial ground contact and this leave no time for mechanosensory feedback mechanisms to prevent injury, which suggests that a different mechanism may have occurred after WBV in this study.

Some gender differences in the timing of H and RF muscle activation have also been demonstrated in the literature (11,30). However, both seem to employ a similar sequence of muscle activation (5). The ratio of the H to the RF activation is reportedly important as a risk factor of ACL injury (48). In a study by Hanson et al. (17), lower H-to-quadriceps activation ratios were found in female players than in male soccer players during a standardized side-cutting maneuver. This finding is consistent with those of others who report higher H-to-quadriceps activation ratios for men, compared with that for women, during functional movements (34,35). However, in this study, no significant differences were found in activation ratios between men and women before or after the WBV.

Finally, it was suggested that both muscle stiffness and muscle coactivity may also contribute to knee stability (21). Some authors reported that H stiffness is significantly greater in men than in women, and this may potentially contribute to longer electromechanical delay and a lesser rate of muscle force production in response to joint perturbation (4). Voluntary responses are too slow to protect the joint. However, reflexive muscular activation may be sufficient to elicit a protective stiffening response (41). In fact, the greater the muscle activation, the greater the joint stiffness (10). The results of this study indicate that after WBV, there were no significant differences, although a decrement in postactivation frequency H values was found in women together with an increase in RF activity. This may indicate that the women were attempting to use their quadriceps muscles to maintain the position of the knee.

Both preparatory and reactive muscle activities assist in regulating muscular stiffness, and increased muscular stiffness provides greater joint stability and protection against joint injury (38). In this sense, WBV was suggested to control knee position during dynamic movement by the nervous and muscular systems, increasing the coactivation of the muscles surrounding the joint (32). However, in this study, these different muscle activation strategies between genders are not apparent, which may indicate that the vibratory stimulus was not enough to induce muscle coactivation. These results contrast with those of Moezy et al. (32) who found that WBV resulted in a greater amount of antagonist coactivation. One possible explanation for this finding may be the double reciprocal inhibition in which antagonist muscle pairs are simultaneously active (39). Adequate cocontraction of the H during explosive movements is extremely important for dynamic knee joint stabilization (2), and these authors reported that WBV had a greater effect for knee stability than did conventional training because WBV resulted in a greater amount of antagonist coactivation. In addition, WBV may induce the reflex action on gamma motoneurons modulating muscle stiffness, and this might also explain possible gender differences in this phenomenon considering that the subjects had difficulty in controlling force production during vibration and that greater levels of coactivation are needed to control movements, and therefore, this situation may require a greater response of the proprioceptive system (44). Another possible explanation of our results after WBV might be because of improved synchronization of the motor units and improved cocontraction of synergist muscles, which could improve joint stability (21). This explanation may be more suitable attending to the kinetics improvements achieved in this study.

Some authors have reported that knee injury is related to decreased knee flexion at initial contact, increased RF EMG activity and also increased knee valgus during unilateral landings (20,36). One of the most intriguing results of this study is the significant effect of gender on the lower limb acceleration. To our knowledge, this is the first investigation that has evaluated the acceleration suffered by the knee and ankle during landing. As such, direct comparison of our reported values with those of previous literature is not possible. However, Chappell et al. (7) showed that women exhibit greater anterior shear force on the tibia during landing compared with what men exhibit. Gender differences in muscle reflex in response to tibial internal-external rotation and anterior translation of the knee have also been examined (42). The results shown in this study are consistent with those of previous literature but only in the AP axis. However, gender differences have shown that the participating female athletes shown a greater (nonsignificant) ML acceleration than did their counterpart male athletes in both knee and ankle, and this absence of muscle control of ML knee motion has been suggested to result in high valgus knee torques and high GRF (47). These gender differences in joint kinematics suggest that increased dynamic knee valgus contributes to ACL noncontact injury risk in women (48).

When acceleration was assessed after WBV, an increment in the AP axis for the knee was found in men (6%) and women (5%). Kvist (25) indicated that exercise affects tibial translation in a different manner depending on gender, although the authors reported that training resulted in a postexercise increase in tibial translation only in the male athletes. In this study, no gender differences could be found. One possible explanation of the kinetic characteristics found might be related to the fatigue resulting from the WBV because Chappell et al. (7) reported that subjects land with significantly increased peak proximal tibial anterior shear forces, increased valgus moments and decreased knee flexion angles during landings in fatigue conditions, and it was found that fatigue resulted in increased knee internal rotation, adduction, and abduction moments, with the latter being more pronounced in women (29). However, Fagenbaum and Darling (12) interpreted the increased knee flexion acceleration during landing as a potential injury-prevention mechanism; therefore, the observed effect of WBV may play an important role in stabilizing the knee, mainly in women's ML activity. In general, ML muscle control of the knee joint is necessary because medial joint compression may be an ACL protective mechanism because it can avoid excessive abduction displacement (20,33).

In conclusion, women display significantly greater H EMG activity in the preactivation period during single-legged drop landings before WBV than do their male counterparts. In addition, gender differences in the knee flexion angles, GRF and ML acceleration were reported. After WBV, there were no significant differences between men and women. However, women experienced a decrement in knee and ankle ML acceleration with no changes in the EMG data, which may suggest an increase in the synchronization activity of the motor units or even muscle cocontraction.

PRACTICAL APPLICATIONS

Numerous studies have demonstrated gender differences in the performance of single-legged landings, a common athletic maneuver that is important in cutting or jumping. These differences in neuromechanical function and musculotendinous stiffness may contribute to the greater incidence of ACL injury in women (4). Our comparison of kinematics and neuromuscular responses in male and female subjects to a WBV perturbation provides a new insight into the control of knee joint loading. In particular, our results may suggest that interventions based on WBV may offer the potential for increased rate and magnitude of knee muscles recruitment and an increase in the synchronization activity, which has been suggested to reduce the rate of injuries in this particular joint.

This study indicates a possible benefit to using WBV as a preventive activity in actions involving explosive motions (e.g., jumping). However, the gender differences reported in knee stability in response to WBV underline the necessity to perform specific neuromuscular training programs based on WBV together with instruction of the proper technique, which can assist the clinician in understanding the mechanisms necessary to protect the joint and prevent injury under sudden loading conditions. However, more research is needed to fully understand how WBV affects muscle activation and stiffness and possible gender differences. Specifically, the results of this study indicate that WBV affects knee stability in a different manner depending on gender.

Therefore, because of these differences, professionals might consider using this activity with some caution, and the use of WBV should always be determined on an individualized basis.

REFERENCES

1. Abián, J, Alegre, LM, Lara, AJ, Rubio, JA, and Aguado, X. Landing differences between men and women in a maximal vertical jump aptitude test. *J Sports Med Phys Fitness* 48: 305–310, 2008.
2. Bencke, J and Zebis, MK. The influence of gender on neuromuscular pre-activity during side-cutting. *J Electromyogr Kinesiol* 21: 371–375, 2011.
3. Benjaminse, A, Habu, A, Sell, TC, Abt, JP, Fu, FH, Myers, JB, and Lephart, SM. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc* 16: 400–407, 2008.
4. Blackburn, JT, Bell, DR, Norcross, MF, Hudson, JD, and Engstrom, LA. Comparison of hamstring neuromechanical properties between healthy males and females and the influence of musculotendinous stiffness. *J Electromyogr Kinesiol* 19: e362–e369, 2009.
5. Cammarata, ML and Dhaher, YY. Evidence of gender-specific motor templates to resist valgus loading at the knee. *Muscle Nerve* 41: 614–623, 2010.
6. Cardinale, M and Bosco, C. The use of vibration as an exercise intervention. *Exerc Sport Sci Rev* 31: 3–7, 2003.
7. Chappell, JD, Creighton, RA, Giuliani, C, Yu, B, and Garrett, WE. Kinematics and electromyography of landing preparation in vertical stop-jump: Risks for noncontact anterior cruciate ligament injury. *Am J Sports Med* 35: 235–241, 2007.
8. Cowan, SM and Crossley, KM. Does gender influence neuromotor control of the knee and hip? *J Electromyogr Kinesiol* 19: 276–282, 2009.
9. Da Silva-Grigoletto, ME, de Hoyo, M, Sañudo, B, Carrasco, L, and García-Manso, JM. Determining the optimal whole-body vibration dose–response relationship for muscle performance. *J Strength Cond Res*, in press.
10. Dhaher, YY, Tsoumanis, AD, Houle, TT, and Rymer, WZ. Neuromuscular reflexes contribute to knee stiffness during valgus loading. *J Neurophysiol* 93: 2698–2709, 2005.
11. Ebben, WP, Fauth, ML, Petushek, EJ, Garceau, LR, Hsu, BE, Lutsch, BN, and Feldmann, CR. Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. *J Strength Cond Res* 24: 408–415, 2010.
12. Fagenbaum, R and Darling, WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med* 31: 233–240, 2003.
13. Ford, KR, Myer, GD, and Hewett, TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc* 35: 1745–1750, 2003.
14. Gehring, D, Melnyk, M, and Gollhofer, A. Gender and fatigue have influence on knee joint control strategies during landing. *Clin Biomech (Bristol, Avon)* 24: 82–87, 2009.
15. Griffin, LY, Agel, J, Albohm, MJ, Arendt, EA, Dick, RW, Garrett, WE, Garrick, JG, Hewett, TE, Huston, L, Ireland, ML, Johnson, RJ, Kibler, WB, Lephart, S, Lewis, JL, Lindenfeld, TN, Mandelbaum, BR, Marchak, P, Teitz, CC, and Wojtys, EM. Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *J Am Acad Orthop Surg* 8: 141–150, 2000.
16. Griffin, LY, Albohm, MJ, Arendt, EA, Bahr, R, Beynnon, BD, Demaio, M, Dick, RW, Engebretsen, L, Garrett, WE Jr, Hannafin, JA, Hewett, TE, Huston, LJ, Ireland, ML, Johnson, RJ, Lephart, S, Mandelbaum, BR, Mann, BJ, Marks, PH, Marshall, SW, Myklebust, G, Noyes, FR, Powers, C, Shields, C Jr, Shultz, SJ, Silvers, H, Slauterbeck, J, Taylor, DC, Teitz, CC, Wojtys, EM, and Yu, B. Understanding and preventing noncontact anterior cruciate ligament injuries: A review of the Hunt Valley II meeting, January 2005. *Am J Sports Med* 34: 1512–1532, 2006.
17. Hanson, AM, Padua, DA, Troy, BJ, Prentice, WE, and Hirth, CJ. Muscle activation during sidestep cutting maneuvers in male and female soccer athletes. *J Athl Train* 43: 133–143, 2008.
18. Harmon, KG and Ireland, ML. Gender differences in noncontact anterior cruciate ligament injuries. *Clin Sports Med* 19: 287–302, 2000.
19. Hermens, HJ, Freriks, B, Merletti, R, Stegeman, D, Blok, J, and Rau, G. *European Recommendations for Surface Electromyography, Results of SENIAM Project* (8th ed.). Enschede, Netherlands: Roessingh Research and Development, 1999.
20. Hewett, TE, Myer, GD, and Ford, KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *Am J Sports Med* 34: 299–311, 2006.
21. Jordan, MJ, Norris, SR, Smith, DJ, and Herzog, W. Vibration training: An overview of the area, training consequences, and future consideration. *J Strength Cond Res* 19: 459–466, 2005.
22. Kernozek, TW, Torry, MR, Van, H, Cowley, H, and Tanner, S. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Med Sci Sports Exerc* 37: 1003–1012, 2005.
23. Kim, KM, Croy, T, Hertel, J, and Saliba, S. Effects of neuromuscular electrical stimulation after anterior cruciate ligament reconstruction on quadriceps strength, function, and patient-oriented outcomes: A systematic review. *J Orthop Sports Phys Ther* 40: 383–391, 2010.
24. Krosshaug, T, Nakamae, A, Boden, BP, Engebretsen, L, Smith, G, Slauterbeck, JR, Hewett, TE, and Bahr, R. Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *Am J Sports Med* 35: 359–367, 2007.
25. Kvist, J. Sagittal tibial translation during exercises in the anterior cruciate ligament deficient knee. *Scand J Med Sci Sports* 15: 148–158, 2005.
26. Kvist, J, Cunningham, D, and Tigerstrand-Wejlemark, H. Gender differences in post-exercise sagittal knee translation: A comparison between elite volleyball players and swimmers. *Knee* 13: 132–136, 2006.
27. Marín, PJ and Rhea, MR. Effects of vibration training on muscle strength: A meta-analysis. *J Strength Cond Res* 24: 548–556, 2010.
28. Markolf, K, O'Neil, G, and Jackson, S. Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med* 32: 1144–1149, 2004.
29. McLean, SG, Felin, RE, Suedekum, N, Calabrese, G, Passerallo, A, and Joy, S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc* 39: 502–514, 2007.
30. Medina, JM, Valovich McLeod, TC, Howell, SK, and Kingma, JJ. Timing of neuromuscular activation of the quadriceps and hamstrings prior to landing in high school male athletes, female athletes, and female non-athletes. *J Electromyogr Kinesiol* 18: 591–597, 2008.
31. Melnyk, M, Kofler, B, Faist, M, Hodapp, M, and Gollhofer, A. Effect of a whole-body vibration session on knee stability. *Int J Sports Med* 29: 839–844, 2008.
32. Moezy, A, Olyaei, G, Hadian, M, Razi, M, and Faghihzadeh, S. A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction. *Br J Sports Med* 42: 373–378, 2008.
33. Myer, GD, Ford, KR, and Hewett, TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol* 15: 181–189, 2005.
34. Nagano, Y, Ida, H, Akai, M, and Fukubayashi, T. Gender differences in knee kinematics and muscle activity during single limb drop landing. *Knee* 14: 218–223, 2007.
35. Padua, DA, Carcia, CR, Arnold, BL, and Granata, KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Motor Behav* 37: 111–125, 2005.
36. Pappas, E, Hagins, M, Sheikhzadeh, A, Nordin, M, and Rose, D. Biomechanical differences between unilateral and bilateral landings from a jump: Gender differences. *Clin J Sport Med* 17: 263–268, 2007.

37. Pflum, MA, Shelburne, KB, Torry, MR, Decker, MJ, and Pandy, MG. Model prediction of anterior cruciate ligament force during drop-landings. *Med Sci Sports Exerc* 36: 1949–1958, 2004.
38. Riemann, BL and Lephart, SM. The sensorimotor system, part I: The physiologic basis of functional joint stability. *J Athl Train* 37: 71–9, 2002.
39. Rothmuller, C and Cafarelli, E. Effect of vibration on antagonist muscle coactivation during progressive fatigue in humans. *J Physiol* 485: 857–864, 1995.
40. Sell, TC, Ferris, CM, and Abt, JP. The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. *Am J Sports Med* 34: 43–54, 2006.
41. Shultz, SJ and Perrin, DH. Using surface electromyography to assess sex differences in neuromuscular response characteristics. *J Athl Train* 34: 165–176, 1999.
42. Shultz, SJ, Perrin, DH, Adams, MJ, Arnold, BL, Gansneder, BM, and Granata, KP. Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. *J Athl Train* 36: 37–43, 2001.
43. Sigward, SM and Powers, CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech (Bristol, Avon)* 21: 41–48, 2006.
44. Sjolander, P, Johansson, H, and Djupsjobacka, M. Spinal and supraspinal effects of activity in ligament afferents. *J Electromyogr Kinesiol* 12: 167–176, 2002.
45. Trans, T, Aaboe, J, Henriksen, M, Christensen, R, Bliddal, H, and Lund, H. Effect of whole body vibration exercise on muscle strength and proprioception in females with knee osteoarthritis. *Knee* 16: 256–261, 2009.
46. Urabe, Y, Kobayashi, R, Sumida, S, Tanaka, K, Yoshida, N, Nishiwaki, GA, Tsutsumi, E, and Ochi, M. Electromyographic analysis of the knee during jump landing in male and female athletes. *Knee* 12: 129–134, 2005.
47. Wikstrom, EA, Tillman, MD, Chmielewski, TL, and Borsa, PA. Measurement and evaluation of dynamic joint stability of the knee and ankle after injury. *Sports Med* 36: 393–410, 2006.
48. Yamazaki, J, Muneta, T, Ju, YJ, and Sekiya, I. Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls. *Knee Surg Sports Traumatol Arthrosc* 18: 56–63, 2010.
49. Zazulak, BT, Ponce, PL, Straub, SJ, Medvecky, MJ, Avedisian, L, and Hewett, TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther* 35: 292–299, 2005.
50. Zeller, BL, McCrory, JL, Kibler, WB, and Uhl, TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med* 31: 449–456, 2003.