Journal of Athletic Training 2018;53(3):255–261
doi: 10.4085/1062-6050-2-17

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# Differences Between Men and Women in Balance and Tremor in Relation to Plantar Fascia Laxity During the Menstrual Cycle

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***Context:*** Although much attention has been paid to the effect of estrogen on the knee ligaments, little has been done to examine the ligaments in the foot, such as the plantar fascia, and how they may be altered during the menstrual cycle.

***Objective:*** To (1) examine sex differences in plantar fascia thickness and laxity and postural sway and (2) identify any menstrual cycle effects on plantar fascia laxity, postural sway, and neuromuscular tremor between menstruation and the ovulation phase.

***Design:*** Case-control study.

***Setting:*** Research laboratory.

***Patients or Other Participants:*** Fifteen healthy women (age = 25.9 ± 1.8 years) and 15 healthy men (age = 27.3 ± 2.0 years) volunteered to participate in this study.

***Intervention(s):*** We asked participants to perform 8 balance tasks on a force platform while we assessed postural sway and tremor.

***Main Outcome Measure(s):*** Plantar fascia length and thickness unloaded and loaded with body weight were measured via ultrasound. Postural sway and tremor were measured using a force platform.

***Results:*** Plantar fascia length and thickness with pressure were greater in ovulating women compared with men ($P < .001$), but no differences were found between women during menstruation and men. Postural sway and tremor were greater at ovulation than during menstruation ($P < .05$), and men had less sway than ovulating women on the 3 most difficult balance tasks ($P < .01$).

***Conclusions:*** Plantar fascia laxity was increased and postural sway and tremor were decreased at ovulation compared with menstruation in women. Postural sway and tremor in men were the same as in women during menstruation. These findings support the need to be aware of the effect of sex hormones on balance to prevent lower extremity injuries during sport activities.

***Key Words:*** estrogen, foot, ligaments, postural sway, sex differences

**Key Points**

- Women had more laxity in the main ligaments of the foot at ovulation compared with menstruation.
- Increased laxity may cause the higher incidence of athletic injuries in women at ovulation.

The plantar fascia is a long, thin, supportive ligament located in the arch of the foot.[1,2] It is a thick, fibrous connective tissue that originates at the medial tuberosity of the calcaneus and inserts into the proximal phalanges.[2] The plantar fascia carries about 10% to 14% of the total load of the foot[3] and plays a crucial role in dynamic function during walking and running. The plantar fascia elongates during the contact phase of gait by about 9% to 12% under full body weight.[4] The elastic properties of the plantar fascia change according to load and may also vary with tissue laxity.[4]

Generally, women are believed to sustain 2 to 8 times more noncontact anterior cruciate ligament (ACL) injuries than men.[5–7] Previous authors[8–11] have shown that these injuries were due to ACL laxity caused by changes in body temperature during the menstrual cycle and the effect of 17-β estradiol receptors in connective tissue. An increase in core and shell temperatures is associated with the latter half of a regular menstrual cycle.[12–14] Therefore, both estrogen and core temperature may exert complex effects on ligamentous laxity.[15,16]

In women who are not on oral contraceptives or past menopause, estrogen fluctuates throughout the normal menstrual cycle.[17] When estrogen peaks, general laxity develops in many ligaments in the body; at the time of ovulation, laxity increases in the ACL and posterior cruciate ligament.[9] Increased knee ligament laxity in female runners at ovulation requires stabilization via increased muscle activity in the flexors and extensors; in contrast, the knee has less flexibility when running during menstruation.[8,18] Laxity of the knee and other ligaments in women at ovulation has been associated with increased injuries in female athletes.[19–21] Estrogen relaxes the collagen cross-bridges in ligaments and alters actomyosin ATPase activity in skeletal muscle. Even if estrogen has no central neuromuscular effects, the relaxation in ligaments and slowing of muscle-contraction speed is compensated for by more muscle activity to maintain motor control at joints such as the knee.[8,18]

Greater postural sway during ovulation than in the early follicular phase (menstruation) has been reported.[22] This could be explained by the complex interaction between knee and ankle laxity as noted earlier. Ericksen and

Gribble[23] found less ankle stability in women than in men but reported no effects of the menstrual cycle. In another study,[24] altered neuromuscular-control strategies in the lower leg at ovulation were correlated with lower leg injuries and motor control during hopping. Similarly, strain on the Achilles tendon was greater in women with a normal menstrual cycle and disappeared when women used oral contraceptives.[25,26]

Although the effects of estrogen on the knee ligaments and Achilles tendon have been described, few researchers have focused on the ligaments of the foot, such as the plantar fascia, and how they may be altered during the menstrual cycle. If the same estrogen receptors are found in ligaments, the plantar fascia will predictably be more flexible at ovulation.

Therefore, the primary purpose of our study was to investigate sex differences in plantar fascia thickness and laxity and postural sway. We hypothesized that postural sway and neuromuscular tremor would be greater in women than in men because of greater plantar fascia laxity. A secondary objective was to determine the effect of the menstrual cycle on plantar fascia laxity, postural sway, and neuromuscular tremor by comparing the 2 phases of the menstrual cycle (menstruation versus ovulation), when estradiol concentration was lowest and highest, respectively.

## METHODS

### Participants

Thirty-six young, healthy male and female recruits between the ages of 18 and 30 years volunteered to participate in this study. The 19 females and 17 males all had a body mass index between 18 and 30 kg/m$^2$, and all performed <150 minutes of moderate or lighter physical activity per week (*physically active*).[27] Participants were excluded if they had a history of cardiovascular disease, neuromuscular disorder, diabetes, vestibular disease, equilibrium disorder, or any lower extremity joint injury or pain at the time of testing. Female participants had to have a regular menstrual cycle (cycle length = 26–35 days), no history of pregnancy, and no use of any medication that would affect the sex hormones. This study was approved by the Institutional Review Board at Loma Linda University, and all participants signed a statement of informed consent before beginning the study.

### Instrumentation

Foot length was measured with the participant standing on a polypropylene sheet coated with talcum powder. This allowed the bare foot to assume a natural shape because the powder reduced friction. We used a digital caliper to measure foot length and width and arch height.

Musculoskeletal ultrasound is a practical method for confirming the diagnosis of plantar fasciitis by measuring plantar fascia thickness. Plantar fascia thickness was evaluated sonographically using the L14-6 MHz linear array transducer Sonosite Titan Ultrasound System (Fujifilm Sonosite Inc, Bothell, WA) and acoustic coupling gel applied to the plantar surface. The plantar fascia was examined with the patient in 2 positions: prone, with the affected foot hanging over the edge of the examination table and the ankle in neutral position, and while standing on a platform. The ultrasound probe was applied vertically to the plantar aspect of the heel. The sagittal thickness of the proximal insertion of the plantar fascia was measured at a standard reference point 5 mm from the proximal insertion at the anterior aspect of the inferior border of the calcaneus.

The thickness of the plantar fascia was measured during loading of the foot. The participant lay supine for measurement of plantar fascia thickness. A leather strap was applied across the toes; the thickness of the plantar fascia was measured with no pressure and 20, 40, and 50 pounds of pressure applied to dorsiflex the foot with the ankle at 90°. The thickness of the plantar fascia was determined by having the participant stand on a platform with a small hole positioned under the arch. Musculoskeletal ultrasound was performed through the heel to measure the thickness of the plantar fascia.

Tactilus pressure-mapping sensors (Sensor Systems, Morristown, NJ) were used to measure weight distribution during standing. Participants stood on the sensors for 2 minutes to allow the distribution of foot pressure to be mapped.

Postural stability was assessed using a force platform. The displacement of the center of pressure (CoP), mean CoP position, length of the CoP path, sway velocity, area of CoP path, and root mean square area have been used to determine postural sway. Some investigators[28,29] used the coefficient of variation (CV) of weight displacement as a measure of postural sway. In this study, we used the CV of the polar vector of weight displacement to measure postural sway. Tremor was assessed in the 8-Hz and 24-Hz bands as variation of movement on the platform. The validity and reliability of this force platform were established in previous studies.[22,30] Four stainless steel bars, each with 4 strain gauges (model FLA-6, 350-17; Tokyo Sokki Kenkyujo Co, Ltd, Tokyo, Japan), were mounted at the 4 corners under the platform. The output of the 4 Wheatstone strain gauge bridges was amplified by a low-level biopotential amplifier (model M35; BIOPAC Systems, Inc, Goleta, CA) and digitized through a 24-bit A/D converter. The sampling rate was 1000/s.[30] To calculate the load and the COP of force on the platform, the output of the 4 sensors was used to measure the X and Y coordinates of the participant's center of gravity. The data were then converted to a movement vector, providing magnitude and angular displacement. By averaging this movement vector over 6 seconds, we obtained the mean and standard deviation for this measure. From this, the CV of the polar coordinate was calculated (standard deviation ÷ mean × 100%) as a measure of postural sway.[30] The average CV for each task was determined over a 5-second sample of the data.

Eight quiet-standing balance tasks were conducted. Sensory variables such as vision, base of support, and surface compliance were altered individually or simultaneously in the balance tasks. Two visual conditions (eyes open and eyes closed) altered the visual input in the balance tasks. Two surfaces (firm and foam) altered the somatosensory input (Table 1). Participants were asked to stand with feet either apart or in tandem (feet in a heel-toe position with the nondominant foot in front).[31]

Table 1. Eight Balance Tasks[a]

| Station | Position | No. of Altered Factor(s) | Sensory Factor(s) |
|---|---|---|---|
| TEO-FIRM | Tandem standing<br>Eyes open<br>Firm surface | 1 | Base of support |
| FAEO-FOAM | Feet apart<br>Eyes open<br>Foam surface | 1 | Surface compliance |
| FAEC-FIRM | Feet apart<br>Eyes closed<br>Firm surface | 1 | Vision |
| TEO-FOAM | Tandem standing<br>Eyes open<br>Foam surface | 2 | Base of support<br>Surface compliance |
| TEC-FIRM | Tandem standing<br>Eyes closed<br>Firm surface | 2 | Base of support<br>Vision |
| FAEC-FOAM | Feet apart<br>Eyes closed<br>Foam surface | 2 | Vision<br>Surface compliance |
| TEC-FOAM | Tandem standing<br>Eyes closed<br>Foam surface | 3 | Base of support<br>Vision<br>Surface compliance |

[a] Table is adapted with permission from Tse YY, Petrofsky JS, Berk L, et al. Postural sway and rhythmic electroencephalography analysis of cortical activation during eight balance training tasks. *Med Sci Monit*. 2013;19:175–186.

## Procedures

Female participants were tested twice during 1 full menstrual cycle: once during menstruation (1 to 3 days after the onset of menstruation) and once during ovulation (12 to 14 days after the onset of menstruation). When screened for the study, they were asked to report the days of their cycle. As body core temperature fluctuates during the day and might affect connective tissue laxity,[9,10] all measurements were performed during the same timeframe on each test day. As males do not experience a menstrual cycle, they were tested only once.

After the participants arrived at the laboratory each day, they rested comfortably in a temperature-regulated room at 25°C for 20 minutes to stabilize body temperature in a neutral environment.

For plantar fascia laxity, 2 different measurements were taken. First, the foot was loaded with 2 weights (half body weight and full body weight), and foot length from the longest toe to the heel was measured on a powdered polypropylene sheet. The thickness of the plantar fascia was also measured with no load and full body weight to assess the laxity of the plantar fascia. Finally, 8 balance tasks were assessed using a balance platform.

## Sample-Size Estimation

Sample size was estimated using G-Power 3.1 software (Heinrich Heine University Düsseldorf, Düsseldorf, Germany). A reasonable expectation would be the detection of an effect size of 0.3 with repeated measures, an α error probability of .05, and power of 0.90.[10] A total sample size of 30 was required to show statistical significance when clinically significant differences were at 92% power. We increased the sample size by 20% to account for withdrawals.

Table 2. Characteristics of Each Group (N = 30)

| Characteristic | Women (n = 15) | Men (n = 15) | *P* Value[a] |
|---|---|---|---|
| | Mean ± SD | | |
| Age, y | 25.9 ± 1.8 | 27.3 ± 2.0 | .09 |
| Height, cm | 164.3 ± 5.4 | 173.5 ± 4.2 | <.001 |
| Weight, kg | 59.6 ± 7.5 | 73.3 ± 5.5 | <.001 |
| Body mass index, kg/m² | 22.0 ± 2.6 | 24.3 ± 1.7 | .07 |
| Cycle length, d | 28.9 ± 2.3 | Not applicable | Not applicable |
| Physical activity level, min/wk | 98.6 ± 15.2 | 107.5 ± 18.5 | .12 |

[a] Independent *t* test.

## Statistical Analysis

Data were summarized as means and standard deviations using SPSS (version 22.0; IBM Corp, Armonk, NY). Normality of variables was assessed using the 1-sample Kolmogorov-Smirnov test. Basic characteristics between the groups were compared using independent *t* tests. We conducted a paired *t* test or Wilcoxon signed rank test to compare foot length and plantar fascia thickness during ovulation and menstruation. An independent *t* test or Mann-Whitney *U* test was used to compare variables in men with those in women during phases of the menstrual cycle (ovulation or menstruation). One-way repeated-measures analysis of variance was calculated to examine mean postural sway and tremor for 8 balance tasks in men and at each phase of menstruation in women. The Bonferroni pairwise test for multiple comparisons was applied to determine the mean values of the variables for any 2 balance tasks. The level of significance was set at $\alpha = .05$.

## RESULTS

Thirty participants (15 in each group) completed the study. Three participants withdrew because of issues related to their menstrual cycle, and 3 withdrew due to scheduling difficulties. The general characteristics of participants are described in Table 2.

## Foot Length

The change in foot length when standing on 2 legs (half body weight) or 1 leg (full body weight) was different between men and ovulating and menstruating women ($F_{2,42} = 5.235$, $P = .009$). Foot length changed more in ovulating women than in men (5.049 ± 2.502 versus 2.792 ± 2.074, 95% confidence interval [CI] = 0.86, 3.89) and in menstruating women (5.049 ± 2.502 versus 3.497 ± 1.364, 95% CI = 0.05, 3.05). However, the mean change in foot length was not different between men and menstruating women (2.792 ± 2.074 versus 3.497 ± 1.364, 95% CI = –0.68, 2.31).

## Plantar Fascia Thickness

The plantar fascia thickness without applied pressure in women at ovulation was not different compared with women during menstruation (0.215 ± 0.034 versus 0.217

**Table 3. Plantar Fascia Thickness Differences in Women Between Ovulation and Menstruation**

| Condition | Ovulation | Menstruation | 95% Confidence Interval | *P* Value[a] |
|---|---|---|---|---|
| | Mean ± SD | | | |
| No pressure | 0.215 ± 0.034 | 0.217 ± 0.029 | −0.015, 0.011 | .731 |
| Pressure applied | 0.165 ± 0.021 | 0.187 ± 0.029 | −0.033, −0.013 | <.001 |
| Differences[b] | 0.050 ± 0.026 | 0.029 ± 0.011 | 0.005, 0.036 | .012 |

[a] Paired *t* test.
[b] Plantar fascia thickness differences with and without pressure.

± 0.029, 95% CI = –0.015, 0.011; Table 3). However, when a load was applied to the foot, mean plantar fascia thickness differed between ovulating and menstruating women (0.165 ± 0.021 versus 0.187 ± 0.029, 95% CI = –0.033, –0.013; Table 3). When pressure was applied, women during menstruation and men did not differ (0.187 ± 0.029 versus 0.191 ± 0.031, 95% CI = –0.027, 0.019), but ovulating women and men were different (0.165 ± 0.021 versus 0.191 ± 0.031, 95% CI = –0.048, –0.007). The plantar fascia thickness without pressure in men was not different than in women during menstruation or ovulation (0.228 ± 0.037 versus 0.212 ± 0.030, 95% CI = –0.041, 0.009; 0.228 ± 0.037 versus 0.215 ± 0.034, 95% CI = –0.039, 0.013, respectively).

## Postural Sway

When 1 factor was altered in the male group (ie, feet apart, eyes open, on foam compared with a firm base of support), postural sway increased 1.5-fold (0.035 ± 0.024 versus 0.056 ± 0.024, 95% CI = –0.09, –0.03). When 2 factors were altered (ie, feet apart, eyes closed on a foam surface compared with feet apart, eyes open, on a firm surface), postural sway increased almost 3-fold (0.035 ± 0.024 versus 0.107 ± 0.007, 95% CI = –0.16, –0.06). Finally, with 3 factors altered (ie, eyes closed, tandem standing on foam), the sway increased about 5.6-fold (0.035 ± 0.024 versus 0.199 ± 0.108, 95% CI = –0.27, –0.15) for the easiest task. Women had a similar pattern on within-subject analysis during 8 balance tasks. In women, other than for the 2 easiest tasks, more sway was present at ovulation than during menstruation ($P < .05$; Figure 1). Men and menstruating women did not differ ($P > .05$) except during tandem standing with eyes closed on a firm base ($P = .01$), but men demonstrated less sway than ovulating women with feet apart, eyes closed, on a firm base ($P = .001$) on the 3 most difficult tasks ($P < .001$; Figure 1).

## Tremor

Tremor measured at 8 and 24 Hz is illustrated in Figures 2 and 3, respectively. Both the 8- and 24-Hz tremors were different across the 8 balance tasks in men and in women at ovulation and menstruation ($P < .001$; Figure 3). Men and menstruating women did not differ on the 8 balance tasks, and menstruating women demonstrated less tremor than did ovulating women for the 3 most difficult balance tasks at the 8-Hz bandwidth ($P < .01$). The same results were seen for the 24-Hz tremor, as shown in Figure 3.

## DISCUSSION

Given the laxity changes about the knee during running in women, it can be hypothesized that similar laxity changes about the foot should be quantifiable by loading the foot and examining thinning of the plantar fascia. Moreover, balance and motor control should be altered if the plantar fascia becomes more lax at ovulation.[22]

We showed that plantar fascia thickness, when not under load, did not change when comparing menstruating with

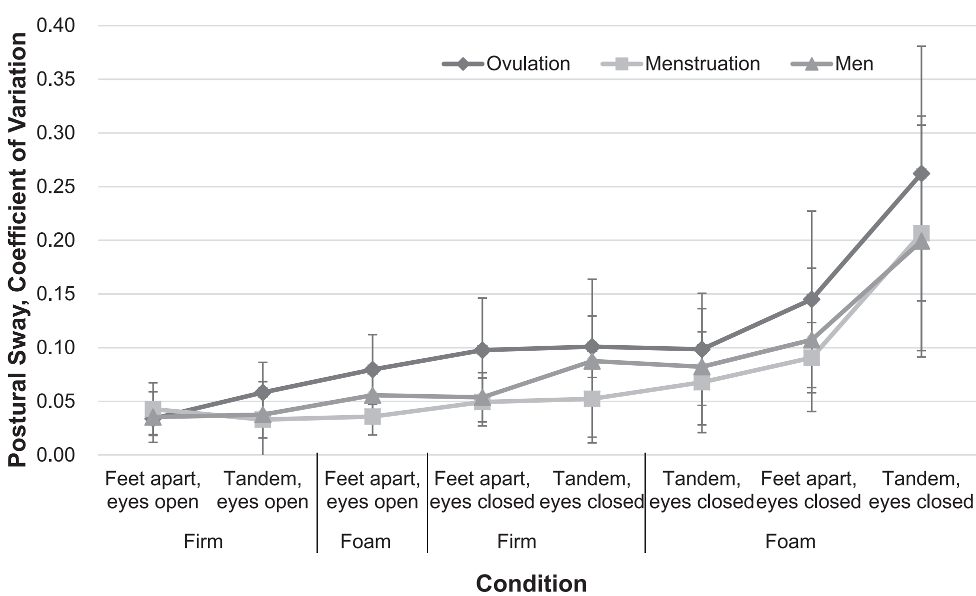


**Figure 1. The coefficient of variation of postural sway during 8 balance tasks in men and in women at menstruation and ovulation.**

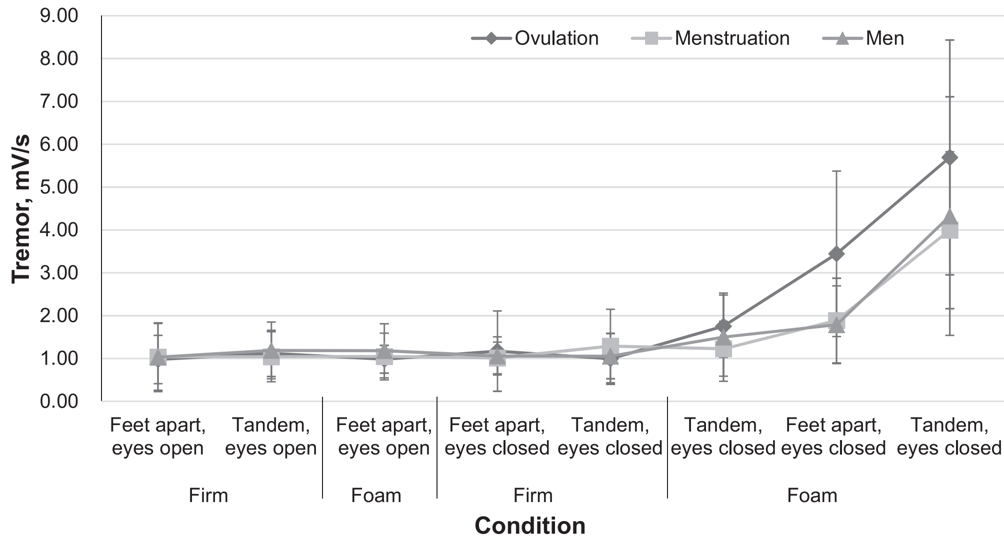


**Figure 2. The 8-Hz tremor during 8 balance tasks in men and in women during menstruation and ovulation.**

ovulating women. However, when a load was applied by having the participant stand on 1 foot, the plantar fascia thinned more and the foot lengthened more during ovulation than during menstruation. A logical conclusion is that, because more plantar fascia thinning and stretching occurred at ovulation than at menstruation, elasticity increased at ovulation. Authors of a previous study[32] showed that women had more laxity in the plantar fascia than men under both static and dynamic conditions. However, they did not examine women in relation to the menstrual cycle. Although the results agreed for much of the menstrual cycle, we did not find such a difference during menstruation, a factor not accounted for in the prior study.

Thus, as was the case for the ACL, the increased laxity made the foot more mobile. The change in thickness of the plantar fascia in men was statistically the same as in women during menstruation, again showing a change in laxity in women at ovulation.

The balance tests did not isolate the foot for testing. However, control of the ankle and knee is a major contributor to balance. Sway was much worse during ovulation than during menstruation. Sway in men was similar to that in women at ovulation. Our findings then differ from another report[23] on balance during the menstrual cycle. However, those investigators examined balance from 5 days before to 5 days after ovulation. As estrogen peaks at ovulation, these measurement times may have masked the results.[23]

Another contributor to sway may be the increased body temperature seen at ovulation.[33] This would also increase laxity in the plantar fascia and other tendons and ligaments and contribute to the increased sway as tendons and ligaments are highly susceptible to small increases in temperature.

However, it was interesting that tremor, a measure of peripheral motor control (spindle error loop), at 8 Hz was greater at ovulation for the 2 most difficult balance tests. Tremor is usually altered by changes in spindle reflex loop

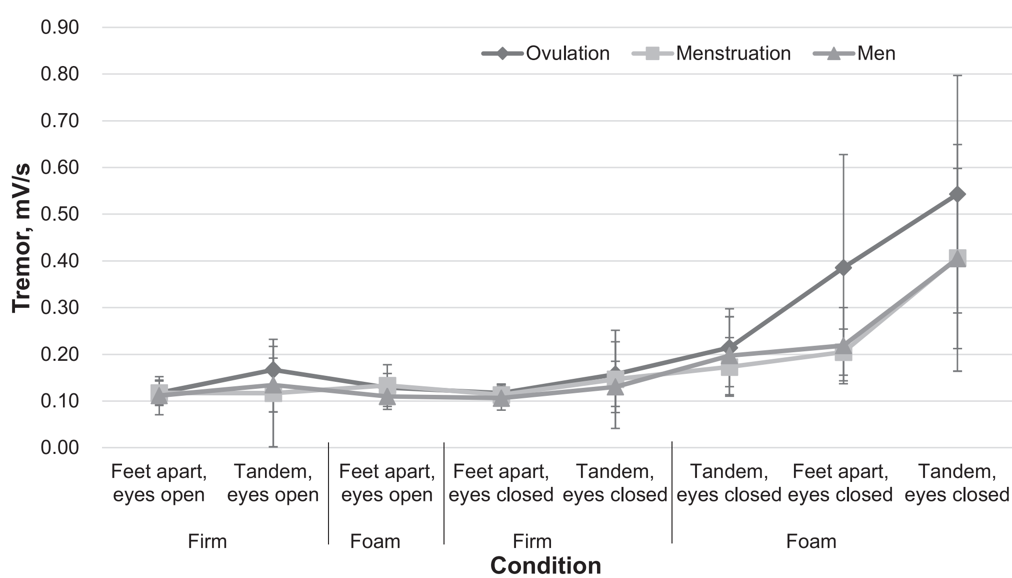


**Figure 3. The 24-Hz tremor during 8 balance tasks in men and in women during menstruation and ovulation.**

times and the viscoelastic properties of tendons and ligaments.[34,35] Tendons form a series of elastic components in muscle,[36] and changes in laxity can alter both the amplitude and frequency of tremor.[35] The data for men were the same as those for women during menstruation. The same result was observed for central tremor (central motor loop error, 24-Hz tremor). The effects of the menstrual cycle on the 8-Hz tremor are probably associated with the increase in tendon laxity due to estrogen, a concept that agrees with the findings of earlier studies showing that changes in tendon laxity can alter tremor. Although fatigue can alter tremor, the participants experienced no fatigue,[37] as the trials lasted only minutes.

Another contributor to changes in tissue laxity that can alter tremor may be the increase in tissue temperature seen at ovulation, when the central and peripheral tissue temperatures can rise more than 1°C.[33] Increased tissue temperature makes tendons and ligaments more elastic.[9,15,38,39] This would also then increase tremor at ovulation in women. The 24-Hz tremor cannot be explained by this mechanism at ovulation. However, 17-β estradiol receptors in the brain may also affect central motor control, eg, in the hippocampus[40] and cerebellum.[41]

Our results agree with previous work by showing that plantar fascia laxity increased when estrogen increased, which also affected ligaments and tendons. However, our study was limited by including only 15 female participants, measuring only 2 time points during the menstrual cycle, and relying on self-reported menstrual cycle information. A comprehensive analysis may yield additional interesting findings by sampling data every 3 to 4 days. Furthermore, stabilizing the foot and leg temperature before measurement would eliminate the contribution of temperature and show the effect of estrogen alone.

## CONCLUSIONS

Plantar fascia laxity was greater at ovulation compared with menstruation in women, and men's plantar fascia laxity was the same as that of menstruating women. Also, women's postural sway and tremor were greater at ovulation, when plantar fascia laxity was increased, than during menstruation. Greater postural sway and tremor could be potential risk factors for falling and lower extremity injuries. These findings support the importance of being aware of the effects of sex hormones on balance for the purpose of preventing lower extremity injuries during sport activities.


## ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea grant funded by the Korean government (Ministry of Science, ICT & Future Planning; No. 2017R1C1B5017867).


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