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Aerobic capacity and isometric knee flexion strength fatigability are related to knee kinesthesia in physically active women

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Abstract.
BACKGROUND: Fatiguing exercise may impair functional joint stability and increase injury risk. Musculoskeletal and physiological characteristics are related to fatigue, but their relationship with proprioceptive changes following fatigue is unknown.
OBJECTIVE: To establish the relationship between strength and physiological characteristics and changes in knee proprioception following fatigue.
METHODS: Physically active women (N = 20, 28.7 ± 5.6 years, 165.6 ± 4.3 cm, 61.8 ± 8.0 kg) underwent isokinetic knee strength and peak oxygen uptake (VO2peak)/lactate threshold (LT) testing during Visit 1, and threshold to detect passive motion (TTDPM) and isometric knee strength testing before and after fatiguing exercise during Visit 2.
RESULTS: Fatigue demonstrated no effect on TTDPM despite a decrease in isometric knee flexion strength ($P < 0.05$). Strength and physiological variables were not significantly correlated with changes in TTDPM. VO2peak was correlated with pre-fatigue ($r = -0.50$) and post-fatigue ($r = -0.52$) TTDPM into extension ($P < 0.05$), and further analyses demonstrated that post-fatigue changes in isometric knee flexion strength and strength ratio were related to post-fatigue changes in proprioception ($r = -0.62$ and -0.40, $P < 0.05$).
CONCLUSIONS: Physically active women with higher aerobic capacity exhibit enhanced knee proprioception, and may benefit from training to strengthen and reduce the fatigability of the knee flexors following intense exercise, as these changes were associated with reduced proprioception.

Keywords: Proprioception, fatigue, kinesthesia, aerobic capacity, knee injury, strength

1. Introduction

Fatiguing exercise has been widely investigated because it may result in impaired functional joint stability, decreased performance, and increased risk of unintentional musculoskeletal injury [1–3]. Fatigue plays an important role in the onset of unintentional muscu-

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loskeletal injury during practices and games [4–6] with a majority of these injuries occurring in the lower extremity [7]. Injuries often occur during preseason training activities when athletes are less conditioned because they are likely more susceptible to fatigue and may be unaccustomed to the movement patterns of the sport [8]. Other research has found that injuries occur more frequently in games than practices, especially when fatigued in the later stages of games [5,6], and may be related to diminished sensorimotor function and slower reaction times. Female athletes are at increased risk of incurring a musculoskeletal injury compared to male athletes [7], especially in the lower extremity.

Fatigue has been identified as a risk factor for injury in many sports injury surveillance studies [4–10], and understanding the underlying mechanisms and the impact on neuromuscular control and proprioception may help better explain why fatigue may increase the risk of injury. During practice and games, athletes and trained individuals experience a combination of peripheral and central fatigue [11]. Peripheral fatigue is operationally defined as changes that occur inside the muscle fiber during exercise [12] and central fatigue as specific alterations in central nervous system (CNS) function that result in a failure to maintain required or expected force or power output [13]. Many factors may contribute to the onset of peripheral fatigue, including muscle fiber type, muscle temperature, metabolic changes, pH level, and type of muscle contraction [12]. These intramuscular changes may result in reduced force production, decreased velocity of shortening, and slowed relaxation [14]. Central fatigue is hypothesized to be elicited by alterations in neurotransmitters, cerebral oxygen delivery deficits, hyperthermia, homeostatic regulation, and psychological factors, including perceived exertion [13,15,16]. These factors may contribute to delayed reaction times and impaired motor performance [15]. Poor muscle conditioning may contribute to early onset of fatigue and increased injury risk [7,17], suggesting a potential relationship between musculoskeletal strength and changes in joint proprioception following fatiguing exercise because better muscle conditioning may delay the onset of peripheral fatigue. Early onset of fatigue may be attributed to poor aerobic and anaerobic conditioning, as studies have suggested that early season injury may be attributed to fatigue associated with lack of conditioning [8].

Since the negative changes elicited with the onset of fatigue at both the peripheral (muscle) and the CNS level may result in decreased sensorimotor function, researchers have explored the mechanisms of fatigue-induced disturbance of neuromuscular control and proprioception; however, the exact relationship between fatigue and impaired sensorimotor function remains unclear [1–3,18,19]. Peripheral fatigue may negatively impact proprioceptive signals arising from peripheral areas of the body, and these signals are crucial for neuromuscular control, postural stability, and overall functional joint stability [20]. Likewise, the onset of central fatigue may negatively impact proprioceptive information conveyed to higher levels of motor control, including the cerebral cortex, spinal level, brain stem, cerebellum, and basal ganglia [21,22]. Previous research has revealed altered muscle activation patterns and lower extremity kinematics following fatigue [23,24], providing evidence that fatigue has a negative impact on neuromuscular control.

Studies investigating local fatigue protocols have revealed deficits in joint position sense (JPS) and threshold to detect passive motion (TTDPM), defined as the ability to consciously detect relatively slow joint movement [25], following fatigue [2,18,26,27]. Another study examining the effects of local versus generalized fatigue on JPS found that general load resulted in a significant decrease in JPS, while the localized fatigue protocol did not [3]. While the results of these studies are equivocal, it can be inferred that both peripheral and central fatigue may negatively impact joint proprioception, and proprioceptive deficits may ultimately increase risk of unintentional musculoskeletal injury.

In considering modifiable risk factors in the prevention of early fatigue onset and subsequent injury risk, improving musculoskeletal strength and aerobic fitness/anaerobic threshold may enhance an athlete's ability to become more fatigue resistant, maintain optimal sensorimotor function during practice, training, and competition, and, ultimately, decrease risk for unintentional musculoskeletal injury. The purpose of this study was to establish the relationship between musculoskeletal and physiological characteristics related to the onset of fatigue in physically active women and changes in proprioception following fatiguing exercise. It is hypothesized that physiological and musculoskeletal characteristics may be related to changes in proprioception following fatiguing exercise, and women with greater aerobic fitness and strength may have less proprioceptive deficits following fatigue.

2. Methods

2.1. Subjects

Physically active female athletes were recruited (N = 20, age: 28.7 ± 5.6 years, height: 165.6 ± 4.3 cm, weight: 61.8 ± 8.0 kg, Body Fat: 23.3 ± 5.4%). Subjects were eligible for the study if they were: 1) aged 18–40 years; 2) physically active (i.e. minimum of 250 minutes $\cdot$ week^{-1} of aerobic, strength, or sport activity) for a minimum of six months or more. Subjects were excluded from the study if they: 1) did not meet the above exercise requirements; 2) exhibited lower extremity injury symptoms within the previous 6 months; 3) had lower extremity injury within the past year or lower extremity surgery within the previous 5 years; 4) had a history of ligamentous injury or surgery to either knee; 5) had a medical condition that contraindicated participation in maximal exercise (i.e. cardiovascular, pulmonary, vestibular, neurological, or vascular condition); or if knowingly pregnant. Subjects were recruited from the University community. All study activities were approved by the University's Institutional Review Board prior to implementation of any research procedures.

2.2. Procedures

All research procedures took place at a sports medicine laboratory. Session 1 consisted of a body composition assessment and TTDPM familiarization prior to isokinetic strength and maximal oxygen uptake (VO$_{2max}$)/lactate threshold testing, and Session 2 ($>$ 48 hours after Session 1) consisted of TTDPM and isometric strength testing prior to and following a fatigue protocol. Subjects were instructed not to participate in strenuous exercise within 24-hours and not to consume a meal within 2 hours of each test session.

The BODPOD Body Composition System (Cosmed, Chicago IL) was used to measure percent body fat during Session 1. Body volume was measured until two tests met criteria for consistent tests. Percent body fat was calculated using predicted lung volume and an appropriate densitometry equation [28,29].

The Biodex System 3 (Biodex Medical Inc, Shirley, New York) was used to measure threshold to detect passive motion (TTDPM) of the knee of the dominant limb, defined as the leg used to kick a ball as hard as possible. A similar TTDPM protocol has previously demonstrated high reliability and precision [30]. A TTDPM familiarization session was held during Session 1, and TTDPM was measured prior to and immediate following the fatigue protocol during Session 2. A PresSsion gradient sequential compression unit and compression sleeve (Chattanooga group, Hixson, TN) was used to mitigate tactile sense feedback and was inflated around the lower leg to a constant pressure (40 mm Hg) so that equal sensation was felt over the entire limb. The subject was placed at a starting position of approximately 20 degrees of knee flexion. Subject visual and auditory sensory cues were eliminated with a blindfold, ear plugs and headphones with white noise. The researcher manually selected the randomized direction of motion (clockwise or counterclockwise, 0.25 degrees per second). The subject was instructed to hit the remote button when they were able to detect both motion and identify the direction of motion in either knee extension or flexion. The degrees from the start position until the subject hit the remote button were recorded during 10 repetitions (5 in each direction). A trial was not counted if direction was incorrectly identified. The first three correctly identified angle error measures in the flexion and extension direction were calculated for each test, and the average angle error for each direction was calculated between pre- and post-fatigue (ΔTTDPM).

The Biodex System 3 was also used to measure isokinetic knee strength (con/con, 60 degrees/second) during Session 1 [31] and isometric knee strength during Session 2. Subjects were seated in the chair and secured using padded straps according to manufacturer recommendations and performed three practice repetitions of knee flexion and extension at 50% and 100% maximal effort followed by one minute of rest prior to five maximal effort repetitions of knee flexion and extension. Isokinetic strength was reported as the isokinetic average moment produced across five trials of reciprocal concentric contractions at 60°/second normalized to body weight (kg). Flexion/extension ratios were calculated by dividing the flexion isokinetic average moment by the extension isokinetic average moment.

The ParvoMedics TrueOne 2400 (ParvoMedics Inc., Sandy, UT) was utilized to measure maximal oxygen uptake (VO$_{2Max}$) during Session 1 [32]. Subjects were outfitted with a Polar heart rate monitor strap worn just below the chest level and equipped with a face mask. Subjects performed a five minute warm-up on a treadmill at a pace corresponding with approximately 75% of their test speed. A modified Astrand protocol was utilized [33], with a constant speed and incline that began at 0% and increased by 2% every three minutes until subjects reached volitional exhaustion. Ratings of perceived exertion (RPE) were collected with an OMNI RPE scale at the end of each three-minute stage for overall body (RPE-O), limbs (RPE-L and RPE-A), and chest (RPE-C). A maximal effort was verified by at least two of the following criteria: 1) maximum heart rate during the test achieving within 10 bpm of age-predicted heart rate maximum; 2) a plateau of oxygen uptake values with increasing intensity; 3) respiratory exchange ratio (RER) greater than or equal to 1.1; 4) blood lactate concentration of greater than or equal to 8 mmol/L. Since not all subjects met the criteria for a maximum test, VO_2Peak was reported instead, defined as the highest, 15-second interval of VO_2 data collected during the test.

Lactate threshold was measured during the VO_{2Max} test described previously utilizing the Lactate Pro® Analyzer. A drop of blood was collected via lancet finger stick at the end of each stage. Lactate threshold was determined by plotting a lactate curve and examining the best fit inflection point on the line graph plotted and the first point prior to a greater than 1 mmol increase in lactate. The minute-average of oxygen uptake at the end of the stage corresponding to the lactate threshold was utilized in order to calculate the percent of VO_2 peak (% VO_2 peak) at which lactate threshold occurred.

Isometric strength of the knee extensors and flexors was collected following both pre- and post-fatigue TTDPM during Session 2 with the Biodex isokinetic dynamometer utilizing a similar set-up as described previously. After the subject was fitted to the dynamometer, their knee was auto-flexed to a neutral position of approximately 20 degrees flexion. Subjects were allowed one practice trial to sub-maximally and maximally contract into extension and flexion and followed by one minute of rest prior to executing three maximal trials each in extension and flexion. Each maximal contraction lasted for five seconds and was followed by a five second rest prior to changing direction. Isometric strength was reported as the average peak torque produced across the three trials in each direction normalized to body weight.

The fatigue protocol, adapted from Wilkins et al. [34], was performed during Session 2 and consisted of seven stations: 1) 5-min run at 95% VO_2 pace; 2) 3-min run at 110% VO_2 pace; 3) 2-min of push-ups (modified); 4) 2-min of sit-ups (YMCA partial curl-up); 5) 3-min of 12-in step-ups; 6) 3-min run at 110% VO_2 pace; and 7) 2-min run at 115% VO_2 pace. The push-ups were performed in the modified position on the subject's knees. For the curl-ups, the subject began with knees bent at a 30 degree angle and feet placed flat on the ground. Subjects curled up with arms extended until their fingertips reached their knees before returning to the start position. Subjects were encouraged to complete as many modified push-ups, curl-ups, and step-ups as possible during Stations 3, 4, and 5. Following Station 7, if the subject was not volitionally fatigued, the station continued by increasing the incline by 1% each minute until volitional exhaustion. OMNI RPE, heart rate, and lactate were measured at the conclusion of each station during a 1-minute break. Maximal effort was verified with perceptual (OMNI RPE criteria), and at least one of two physiological criteria (lactate $>$ 8.0 mmol and heart rate within 10 bpm of maximum).

Table 1
Demographic data

	Mean		SD	95% CI	Median	IQR
Age	28.7	±	5.6	26.1, 31.3	28.5	24.3, 34.7
Height (cm)	165.6	±	4.3	163.6, 167.6	165.5	162.0, 168.0
Weight (kg)	61.8	±	8.0	58.1, 65.5	60.4	55.4, 65.2
BMI (kg/m^2)	22.5	±	2.3	21.4, 23.6	22.1	20.9, 23.3
Body Fat (%)	23.3	±	5.4	20.8, 25.8	22.4	21.7, 27.7

SD: Standard Deviation; IQR: Interquartile Range.

2.3. Statistical analysis

All statistical analyses were performed utilizing IBM SPSS Statistics v.24 (SPSS Inc., Chicago, IL). Normality of all variables was assessed with a Shapiro-Wilk test. For pre- to post-fatigue comparisons, the pre- to post-isometric knee extension strength difference and TTDPM extension and flexion differences violated assumptions of normality, so paired t-tests and Wilcoxon Signed Rank tests were utilized to determine differences in isometric strength and TTDPM from pre- to post-fatigue. Of the strength and physiological variables, only average peak knee extension moment violated assumptions of normality. All TTDPM variables, except for post-fatigue TTDPM in extension, violated assumptions of normality, so Spearman's Rho correlation coefficients were calculated to determine the relationship between isokinetic strength and physiological variables with ΔTTDPM and pre- and post-fatigue TTDPM when at least one variable in the pair violated assumptions of normality; otherwise, a Pearson correlation coefficient was calculated. An *a priori* power analysis indicated 20 subjects were needed to achieve 81.2% power to detect a difference of -0.4 between a null hypothesis of 0.4 and an alternative hypothesis of 0.8 with alpha set at 0.05. Alpha was set at

Table 2
Isokinetic strength and physiological characteristics

	Mean		SD	95% CI	Median	IQR
Knee Extension Strength (Nm)	125.5	±	23.5	114.5, 136.5	132.4	98.5, 146.3
Knee Flexion Strength (Nm)	64.4	±	12.9	58.4, 70.4	62.8	56.7, 75.4
Flexion/Extension Ratio	0.50	±	0.06	0.47, 0.53	0.52	0.46, 0.54
VO_2 Peak (ml/kg/min)	47.1	±	4.6	44.9, 49.3	48.2	43.0, 50.5
Hear Rate Peak (bpm)	187.8	±	11.1	182.6, 193.0	185.0	179.0, 197.3
Lactate Peak (mmol)	8.8	±	2.0	7.9, 9.7	8.8	7.4, 10.4
Lactate at LT (mmol)	4.1	±	0.8	3.7, 4.5	4.1	3.6, 4.6
VO_2 at LT (ml/kg/min)	40.3	±	5.3	37.8, 42.8	39.8	36.3, 45.7
LT (%VO_2peak)	85.4	±	4.8	83.2, 87.6	85.5	83.1, 87.8
Test speed (km/h)	610.5	±	1.0	10.0, 11.0	10.5	10.1, 10.8
End Time (sec)	755.9	±	135.3	692.6, 819.2	780.0	697.5, 870.0

SD: Standard Deviation; IQR: Interquartile Range; LT: Lactate threshold.

Table 3
Isometric strength changes pre- to post-fatigue

	Pre-fatigue				Post-fatigue				Pre-post	95% CI of	Effect
	Mean		SD	Median	Mean		SD	Median	p-value	the difference	size
Knee Extension Strength (Nm)[b]	133.3	±	30.9	128.6	131.7	±	29.5	131.4	0.808	n/a	−0.038
Knee Flexion Strength (Nm)[a]	72.0	±	17.9	67.8	64.9	±	16.7	64.1	0.001*	3.2, 11.1	0.845
Flexion/Extension Ratio[a]	0.55	±	0.11	0.54	0.50	±	0.10	0.41	0.007*	0.01, 0.08	0.672

Paired t-test and Cohen's D[a] or Wilcoxon Signed Rank Test and non-parametric effect size[b] calculated; *Significant difference at the $p < 0.01$ level.

Table 4
TTDPM changes pre- to post-fatigue

	Pre-fatigue				Post-fatigue				Pre-post	Effect size
	Mean		SD	Median	Mean		SD	Median	p-value	
TTDPM Ext (°)	1.54	±	0.96	1.33	1.54	±	0.77	1.53	0.601	−0.083
TTDPM Flex (°)	−1.52	±	1.09	−1.05	−1.51	±	1.51	−1.27	0.469	−0.115

Wilcoxon Signed Rank Test utilized to determine significant differences from pre- to post-fatigue Mean/median values are average of first three correct trials in extension and flexion. Mean/median values are presented as the error from starting position, with all extension results being positive, and all flexion results being negative.

0.05 *a priori.* Effect sizes for paired samples comparisons were calculated utilizing the appropriate equation for parametric or non-parametric analyses [35].

3. Results

Demographic and baseline strength and physiology data are presented in Tables 1–2. As a group, subjects reached near-maximal perceived exertion in their legs, chest, and overall, reached above maximal criteria for blood lactate (> 8.0 mmol), and reached within 10 bpm of age-predicted heart rate max during the fatigue protocol. Isometric knee extension strength was not significantly different after the fatigue protocol, while isometric knee flexor strength and flexion/extension ratio significantly decreased following the fatigue protocol (Table 3).

No significant differences were demonstrated between pre- and post-fatigue TTDPM into extension or flexion (Table 4). No significant correlations were observed between any strength or physiological variables with ΔTTDPM from pre- to post-fatigue in extension or flexion or with pre-fatigue or post-fatigue TTDPM in extension or flexion, except for a significant, negative correlation between VO_2 Peak and both pre-fatigue ($r = -0.50$, $p < 0.01$) and post-fatigue ($r = -0.52, p < 0.05$) TTDPM in the extension direction.

4. Discussion

The purpose of this study was to investigate the relationship between musculoskeletal strength and physiological characteristics with ΔTTDPM following fatiguing exercise. It was hypothesized that subjects with higher levels of strength, aerobic capacity, and lactate threshold would see less deficits in TTDPM following fatiguing exercise. Subjects experienced near maximum levels of perceived exertion and reached maximal physiological criteria during the fatigue protocol and knee flexor musculature strength decreased as a result of the fatigue protocol. However, no statistically significant correlations were demonstrated between any strength or physiological variables and ΔTTDPM.

The fatigue protocol utilized in this study was chosen because it simulated fatigue mechanisms that would have been experienced in a game or practice situation. Subjects experienced near maximum levels of perceived exertion (7–10 on OMNI RPE) and reached maximal physiological criteria ($>$8.0 mmol blood lactate concentration and within 10 bpm of age-predicted heart rate maximum) during the protocol. Results of the pre- to post-fatigue isometric strength assessment of the knee extensors and flexors demonstrated a significant decrease in isometric flexion strength and flexion/extension ratio, indicating that the knee flexor strength decreased as a result of the fatigue protocol.

A significant, moderate [36], negative correlation was observed between VO_{2Peak} with pre-fatigue and post-fatigue TTDPM in the extension direction, indicating that the higher the subject's aerobic capacity, the better their TTDPM score. This finding agrees with previous work demonstrating that highly trained individuals (i.e. collegiate athletes) possess better ability to detect passive motion than less fit individuals [37]. The fact that VO_2 Peak was only correlated with TTDPM in the extension direction may be explained by previous research that has suggested that individuals may possess greater proprioceptive sensitivity during TTDPM when moving in the extension direction, and similar results have been demonstrated previously [19]. This may be due to the fact that the mechanoreceptors within the joint capsule become more sensitive as the joint moves into extension as opposed to when the knee moves into flexion.

No significant correlations were observed between baseline isokinetic knee extension strength, flexion strength, or flexion/extension ratio and ΔTTDPM in extension or flexion following fatigue. Additionally, no significant correlations were found between VO_2 Peak or lactate threshold and ΔTTDPM following fatigue. However, although not part of the primary hypotheses, pre- to post-fatigue differences in isometric knee flexor strength and flexion/extension ratio following fatigue were significantly correlated with changes in TTDPM following fatigue ($r = -0.621$ and -0.403, $p < 0.05$). As evidenced by these findings, perhaps baseline strength measures are not as important as the ability to retain knee flexor strength and maintain an optimal flexion/extension strength ratio in a fatigued state.

The lack of correlation between baseline knee strength and physiological characteristics and changes in proprioception may be theorized in several ways. Strength performance might more strongly correlate with changes in an active mode of proprioception measurement following fatigue because strength and muscle force production would have a greater influence on the mechanoreceptors located within the musculotendinous tissues as well as on the muscle length/rate of length change information within the muscle spindle [21]. Further, it is possible that the fatigue protocol may have not induced enough dysfunction to the central pathways contributing to motor control that would cause TTDPM deficits since it is a passive measurement, which targets the mechanoreceptors not located in the musculotendinous tissues of the knee joint [21].

No significant differences were demonstrated in TTDPM following the fatigue protocol, despite subjects reaching a maximal level of physiological and perceptual fatigue. One explanation is that the fatigue protocol may have induced a decrease in muscular receptor function, which possibly resulted in capsular receptors becoming more strongly stimulated [1]. When the capsule is maximally stressed, there may be an increased response rate of capsular receptors [1,38]. Therefore, fatigue of the knee musculature may have actually enhanced the sensitivity of the mechanoreceptors within the capsule-ligamentous structures of the knee, potentially explaining why significant deficits were not demonstrated in TTDPM following fatigue. Future studies may utilize a control group of sedentary or less-active individuals, as the fatigue protocol may elicit a difference response relative to physically active individuals.

Results of our study are consistent with results from a study by Skinner et al. [1] which also found no significant differences in knee kinesthesia following fatigue. Skinner et al. [1] also utilized a homogenous, highly trained group for testing, and had similar aspects of our fatigue protocol, but did not specifically fatigue the upper body or core. In order to determine level of fatigue, Skinner et al. [1] tested isokinetic strength prior to and following the fatigue protocol, and if subjects did not exceed 10% decrement in work output, they were given additional treadmill exercise. Their TTDPM measurement was conducted at 0.5°/s angular velocity, which is faster than our speed of 0.25°/s, but still aimed to target the slow-adapting mechanoreceptors (Ruffini endings or Golgi-type organs) [39] found within the ligamentous and capsular tissues of the knee [21]. Results demonstrated a decreased ability to reproduce a joint angle, but no significant differences were demonstrated in TTDPM following fatigue. Additionally, post-fatigue TTDPM angle error was less than before fatigue, suggesting improved TTDPM following fatigue.

Our results are partially consistent with results from a study by Rozzi and colleagues [19] which demonstrated no significant changes in proprioception in the flexion direction but significant changes in the extension direction following fatigue. The investigation by Rozzi et al. [19] utilized isolated concentric contractions of the knee extensors and flexors, which may have resulted in decreased proprioception in the extension direction due to the cyclic compressive forces to the knee joint during the isokinetic fatigue protocol. Like Skinner et al. [1], Rozzi et al. [19] moved the knee at a constant angular velocity of 0.5°/s during TTDPM. Since changes to capsuloligamentous structures of the knee following fatigue would likely induce impaired TTDPM, Rozzi et al. [19] also measured joint laxity changes following fatigue. However, the decrease in TTDPM in extension occurred despite no changes in joint laxity following fatigue. Authors concluded that a mechanism other than joint laxity was responsible for the decrements in TTDPM [19], and that isokinetic fatigue did not induce fatigue that would closely simulate joint forces experienced during sport activities [41]. Unlike Rozzi et al. [19], we did not quantify changes in joint laxity from pre- to post-fatigue, so we are, unfortunately, unable to discuss to what extent joint laxity affected our results. Rozzi et al. [19] also demonstrated significantly increased onset of contraction time for the medial hamstring muscle and lateral gastrocnemius muscle following fatigue [19]. Although we did not assess muscle activation as part of this study, our results showed significant decreases in isometric knee flexion-strength and flexion/extension ratio which parallels the decreased activation of the hamstring musculature following fatigue demonstrated by Rozzi et al. [19]. The decreased hamstring strength and flexion/extension ratio following fatigue in our investigation also suggests a similar implication for decreased ability of the hamstring musculature to control anterior tibial translation in a fatigued state, which was also implied by Rozzi et al. [19].

In recent work by Torres and colleagues [26] investigating TTDPM prior to and following exercise at 30 and 70 degrees of knee flexion, no significant differences were found at a 30 degree starting angle one hour after exercise, while TTDPM was altered at the 70 degree starting position one hour post exercise and up to 24 hours post exercise. The investigation by Torres [26] utilized reciprocal eccentric contractions of the knee musculature to induce fatigue. Repeated eccentric contractions likely induced a degree of muscle damage and delayed onset muscle soreness [42], which may explain why deficits in TTDPM at the 70 degree starting position were noticed up to 24 hours post-exercise. Additionally, the deficits were only noticed when the starting position was closer to mid-range than end-range of knee flexion, suggesting that TTDPM deficits may be more pronounced when starting at mid-range, where sensitivity of detecting passive motion may be decreased in comparison to end range. Likewise, the starting angle used in our study was 20 degrees of knee flexion, which is near end-range. Previous work demonstrated that TTDPM was more sensitive at a 15 degree starting angle than 45 degrees in the extension direction [30], and this may be explained by the fact that a 15 degree starting angle is closer to end range of motion where greater tensile stress is placed on the static restraints of the knee. Thus, our results may have shown significant changes in TTDPM had we utilized a starting position closer to mid-range of knee flexion rather than near end-range because the sensitivity of TTDPM may have been too high closer to end-range.

Future studies may test other musculoskeletal characteristics that may be associated with changes in proprioception following fatigue. Previous research has implied that individuals with better muscle development have a better awareness of joint position and motion [37,43], so active individuals and athletes of various ability levels should be considered. Other variables to consider in the future studies examining the relationship between musculoskeletal characteristics and changes in TTDPM following fatigue include time to peak moment, muscular endurance, and torque production decrement following fatigue.

In summary, the purpose of this study was to investigate the relationship between musculoskeletal strength and physiological characteristics with changes in proprioception following fatiguing exercise, and no relationship was demonstrated between these characteristics and proprioception following fatigue. However, baseline aerobic fitness was associated with better proprioception, and decreases in knee flexor strength were associated with a decrement in proprioception following fatigue. Therefore, this study may provide a foundation for future research in the area of fatigue and proprioception since it demonstrated a relationship between increased aerobic capacity and better proprioception. The findings of this study also emphasize the importance of knee flexor strength as it relates to fatigue and knee proprioception. Female athletes may benefit from incorporating resistance training to increase muscular strength and muscular endurance, as well as plyometric and balance training to enhance neuromuscular characteristics. This information may help to guide training and injury prevention programs aiming to mitigate the onset of fatigue during activity and decrease neuromuscular risk factors for athletic injury.

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Conflict of interest

The authors wish to declare no conflict of interest.

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