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Lower Limb Biomechanical Responses During a Standardized Load Carriage Task are Sex Specific

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ABSTRACT

Introduction:
The purpose of this study was to investigate sex-specific lower limb biomechanical adaptations during a standardized load carriage task in response to a targeted physical training program.

Materials and Methods:
Twenty-five healthy civilians (males [$n = 13$] and females [$n = 12$]) completed a load carriage task (5 km at 5.5 km·h^{-1}, wearing a 23 kg vest) before and after a 10-week lower-body–focused training program. Kinematics and ground reaction force data were collected during the task and were used to estimate lower limb joint kinematics and kinetics (i.e., moments and powers). Direct statistical comparisons were not conducted due to different data collection protocols between sexes. A two-way repeated measures ANOVA tested for significant interactions between, and main effects of training and distance marched for male and female data, respectively.

Results:
Primary kinematic and kinetic changes were observed at the knee and ankle joints for males and at the hip and knee joints for females. Knee joint moments increased for both sexes over the 5 km distance marched ($P > .05$), with males demonstrating significant reductions in peak knee joint extension after training. Hip adduction, internal rotation, and knee internal rotation angles significantly increased after the 5 km load carriage task for females but not males.

Conclusion:
Differences in adaptive gait strategies between sexes indicate that physical training needs to be tailored to sex-specific requirements to meet standardized load carriage task demands. The findings highlighted previously unfound sex-specific responses that could inform military training and facilitate the integration of female soldiers into physically demanding military roles.

INTRODUCTION

Carrying external loads comprising essential equipment is a vital part of military training and operations but is associated with increased risk of lower limb injury and performance detriments.[1] External load characteristics are often determined by occupational requirements regardless of individuals' sex, stature, or physical capabilities.[2] Consequently, males and females undertake the same physical tasks while carrying the same standardized loads despite known differences in physical capabilities.[3] Previous military load carriage research has observed limited sex differences, although experimental designs have generally been limited to short duration tasks. As prolonged load carriage evokes larger gait alterations in comparison, further assessments into potential sex-specific responses in lower limb mechanics are required.[4]

Moderate-to-heavy (i.e., <20 kg) load carriage alters lower limb gait patterns and joint loading in both males[5,6] and females.[4] Yet limited sex differences have been shown when carrying absolute loads[7,8], suggesting that adaptive gait mechanics are not adopted by females to compensate for their smaller statures and lesser absolute strength compared to males. Silder et al.[8] reported no sex differences in spatiotemporal measures, peak joint angles, moments, or ground reaction forces (GRFs) when carrying 10%, 20%, or 30% of body mass. The normalization of loads carried may account for the lack of gait adaptations observed, especially as absolute strength and load carriage ability are correlated with body mass.[9] Conversely, Loverro et al.[10] identified that females alter their hip and knee mechanics when carrying medium (15 kg) and heavy (26 kg) loads. As the findings remain equivocal, further investigations are required to clarify if time-course sex differences exist between males and females during standardized load carriage tasks.

Modern military organizations integrate soldiers into mixed sex platoons where completion of the same physical training and physical employment standard tasks are expected.[11] However, known differences in key physical characteristics between sexes (i.e., strength, power, and aerobic fitness)[3] generally place females at a disadvantage for physically demanding military roles. Importantly, performance

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gaps between sexes can potentially be minimized through tailored physical conditioning (e.g., progressive strength training) that targets task-specific demands.[12] For example, the hip joint has been identified as the primary contributor of total joint power (∼60%) toward forward progression during load carriage.[13] Therefore, a training program focused toward strengthening the hip musculature may enhance load carriage performance and attenuate the detrimental effects experienced when carrying external load.

The purpose of this study was to investigate sex-specific adaptations in lower limb biomechanics during a standardized load carriage task and in response to a 10-week evidence-based physical training program. It was hypothesized that (1) lower limb kinematic and kinetic responses will differ between males and females over the distance marched and after training, (2) knee joint moments will be maintained or reduced over the distance marched after training compared to before training, and (3) lower limb net joint powers will be maintained over the distance marched after training compared to before training.

METHODS

Participants

Twenty-five healthy civilians (males [$n=13$]: 22.4 ± 1.7 years, 1.82 ± 0.06 m, 83.91 ± 6.5 kg and females [$n=12$]: 21.3 ± 2 years, 1.7 ± 0.8 m, 64.8 ± 7.5 kg) participated, who had no recent (<6 months) acute or chronic injuries at the time of testing. Previous load carriage experience was not required. Participants who met inclusion criteria provided their written informed consent to the study, which was approved by the Macquarie University Human Research Ethics Committee (Protocols 5201700406 and 5201700997).

Inclusion Criteria

Participants met or exceeded the Australian Army Basic Fitness Assessment standards based on sex and age[11]: a minimum requirement of 70 sit-ups and 40 push-ups (21 push-ups for females) in 2 min each and a minimum of level 7.5 on the beep test. Additional inclusion criteria required a body mass of ≥73 kg for males[14] and ≥55 kg for females.[15]

Physical Training Intervention

Participants completed a 10-week physical training program including resistance focused and weighted walking training sessions per week (Table S1).[16] Resistance training sessions were supervised and delivered by an accredited strength and conditioning coach (accredited Australian Strength and Conditioning Coach). Exercise resistance and weekly progressions were tailored to individual abilities and increased incrementally weekly when the required sets and repetitions were achieved for individual exercises. If this was not possible, the number of repetitions and sets completed were recorded and the resistance was adjusted accordingly. Weighted walking sessions were conducted on a treadmill and were self-directed on a separate day to resistance training sessions. Acute training variables (i.e., distance, speed, and load) incrementally increased over the 10 weeks.

Procedures

A load carriage task, equal to the Australian Army All Corps physical employment standard (5 km at 5.5 km·h^{-1}, wearing a 23 kg vest), was completed before and after the 10-week training program. During laboratory testing sessions, participants wore their own athletic trainers and clothing. Before the load carriage task, retro-reflective markers and marker clusters were placed on each participant's torso and bilaterally on the head, arms, and legs according to previously published methodology.[16,17] Static standing calibration and wand pointer trials determined the 3D positions of 12 marker locations,[18] which were later used to define ankle, knee, and hip joint centers for musculoskeletal model scaling.

Kinetic data (e.g., GRF) were acquired differently between male and female populations. The authors acknowledge that this prohibits making direct statistical comparisons between sexes but determined that the ability to collect continuous kinetic data for females on a force-instrumented treadmill will provide greater insights to biomechanical responses for females. Male participants completed 10 successful overground walking trials immediately before and after the load carriage task (<3-minute lapse between treadmill to overground transition) using in-ground force plates (Type 9281E, Kistler, Germany), sampled at 1,000 Hz. Participants were randomly assigned to strike the in-ground force plate with either their left or right limb. Before walking trials, participants were informed to take their initial step with their allocated limb to avoid influencing foot strike mechanics (e.g., targeting). Successful trials were counted when the participant (1) cleanly struck the force plate with their allocated limb and (2) walked at a speed equivalent to 5.5 km·h^{-1} ± 0.1%, assessed using a portable timing gate system (Kinematic Measurement System, Fitness Technology, Adelaide, SA, Australia). For females, GRF data were acquired for 30 s (sampled at 1,000 Hz) at the beginning (0 km) and end (5 km) of the load carriage task using a force-instrumented treadmill (AMTI force-sensing tandem treadmill, MA, USA). Three-dimensional (3D) motion capture data were acquired synchronously with GRF data during over-ground and treadmill-based walking trials using an eight-camera system (T40, Vicon, Oxford, UK), sampling at 100 Hz.

Data Processing

Raw marker trajectories were reconstructed and gaps (≤10 frames) were filled within Vicon Nexus (Version 2.7.0). Data were then processed using a modified version of MOtoNMS,[19] followed by custom Matlab scripts to define lower limb joint centers within static calibration trials using

Harrington regression equations[20] at the hip and the midpoint of the medial and lateral femoral condyles and malleoli at the knee and ankle, respectively. For males, a single gait cycle per successful trial was determined during over-ground walking trials (such that the results are based on an average of 10 gait cycles) using the vertical GRF data of the foot in contact with the plate (detection threshold $\geq$20 N for heel strike and toe-off events). Spatiotemporal and angular variables for the hip, knee, and ankle were determined using a velocity-based algorithm.[21] For females, an average of 10-30 gait cycles were obtained from each 30-s walking trial at the beginning and end of the load carriage task; the results presented are based on average of these 10-30 gait cycles. Marker trajectories and GRFs were filtered using a fourth-order zero-lag Butterworth low-pass filter (10-Hz cutoff).[22] Marker position data for all walking trials were transformed from the laboratory coordinate system to the global coordinate system used within OpenSim.[23]

Biomechanical Modeling

OpenSim (version 3.3) was used to scale a generic musculoskeletal model[24] to match the gross anatomy of each participant through defined distances between marker pairs and corresponding virtual marker pairs acquired during static standing calibration trials. The model comprised three rotational degrees of freedom (DOF) for the hip, 1 DOF for the knee, and 1 DOF for the ankle. Using the scaled model, inverse kinematics[25] and inverse dynamics tools estimated joint angles, angular velocities, and moments (normalized to each participant's body mass [Nm·kg^{-1}]). From ensemble averages, the 3D peak joint angles (°), ranges of motion (max–min), and angle waveforms across the gait cycle were calculated and used in subsequent statistical analyses. Instantaneous joint power curves (W·kg^{-1}) were split into positive (energy generation) and negative (energy absorption) phases throughout the gait cycle[26] and represented hip, knee, and ankle powers. Positive and negative joint works (J·kg^{-1}) were calculated through defined phases using numerical integration of the instantaneous joint power curves. The sum of positive and negative hip, knee, and ankle joint works determined total positive (W_j^+) and negative (W_j^-) limb work. Individual joint contributions toward total positive work (W_{tot}^+) and total negative work (W_{tot}^-) throughout the gait cycle were identified through expressing W_j^+ and W_j^- as a percentage of W_{tot}^+ and W_{tot}^-, respectively.

Statistical Analysis

Statistical analysis was performed using IBM SPSS statistics version 25 software for Windows (IBM Corp Armonk, NY, USA). Direct statistical comparisons were not conducted between male and female data due to different data collection protocols. A two-way ANOVA with repeated measures tested for significant interactions between, and main effects of training and distance marched for male and female data, respectively. Data normality was confirmed using the Shapiro–Wilk test ($P > .05$). Pairwise comparisons using Bonferroni *post hoc* tests were performed on significant main and interaction effects training and distance marched. For all normally distributed variables analyzed using ANOVA, partial eta-squared (η_p^2) effect sizes are presented. Significance was set at $P < .05$. Partial eta-squared (η_p^2) effect sizes were calculated and interpreted as small (0.01-0.06), medium (0.06-0.14), and large ($\geq$0.14), respectively.[27]

RESULTS

As direct statistical comparisons were not completed due to the difference in data collection techniques, analyzed kinematic and kinetic data will be presented separately for male and female populations.

Spatiotemporal Variables

For males, a significant interaction effect was observed for step width only ($P < .05$, $\eta_p^2 = 0.40$) before training values decreased from pre-to-post-march, whereas values increased over the distance marched after training.

Significant main effects of distance marched were observed for spatiotemporal variables in females (Table I). Stride length ($P = .017$, $\eta_p^2 = 0.42$) and stride time ($P = .017$, $\eta_p^2 = 0.42$) increased over the 5 km march duration. A main effect of training was found for step width where values increased from pre- to post-march after training ($P = .08$, $\eta_p^2 = 0.48$) compared to before training where values remained consistent.

Kinematics

Male data revealed the main effects of distance marched in the sagittal plane only (Table I). Specifically, significant increases in peak hip joint extension ($P < .05$, $\eta_p^2 = 0.73$), peak knee joint flexion angles ($P < .05$, $\eta_p^2 = 0.31$), knee pose at heel strike ($P < .05$, $\eta_p^2 = 0.29$), and mean torso flexion–extension ($P < .05$, $\eta_p^2 = 0.85$) were observed over the distance marched. Conversely, peak hip joint flexion ($P < .05$, $\eta_p^2 = 0.41$) and peak hip pose at heel strike ($P < .05$, $\eta_p^2 = 0.35$) values significantly reduced from pre- to post-march. There was a main effect of training for peak ankle dorsiflexion angle ($P < .05$, $\eta_p^2 = 0.52$), where the peak dorsiflexion angle was maintained over the distance marched before training (7.26° ± 2.46° vs. 7.21° ± 2.70°) but increased from pre-to-post march after training (8.44° ± 2.07° vs. 8.66° ± 2.47°).

Female data demonstrated the main effects of distance marched for kinematic variables in all planes of motion (Table I). Significant increases in peak hip joint extension ($P = .02$, $\eta_p^2 = 0.60$), second flexion peak at the knee joint ($P = .02$, $\eta_p^2 = 0.40$), and peak ankle plantarflexion angles ($P = .049$, $\eta_p^2 = 0.31$) were observed in the sagittal plane. Mean torso flexion–extension angle also increased over the 5 km march ($P = .00$, $\eta_p^2 = 0.80$). An interaction effect

TABLE I. Mean ± Standard Deviation Magnitudes for Spatiotemporal and Kinematic (Sagittal, Frontal, and Transverse Planes) Variables

	Pre-training				Post-training				ES (η_p^2)						
	Male		Female		Male		Female								
	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march	Distance marched		Training		Interaction		
Variable	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Male	Female	Male	Female	Male	Female	
Spatial temporal															
Stride Length (m)	1.61 ± 0.05 (1.58, 1.64)	1.61 ± 0.06 (1.58, 1.64)	1.47 ± 0.07 (1.42, 1.51)	1.50 ± 0.09* (1.44, 1.56)	1.59 ± 0.06 (1.55, 1.62)	1.61 ± 0.07 (1.57, 1.65)	1.47 ± 0.07 (1.42, 1.51)	1.50 ± 0.08* (1.45, 1.55)	0.15	0.42	0.10	0.00	0.20	0.00	
Stride Time (s)	1.06 ± 0.05 (1.03, 1.09)	1.07 ± 0.06 (1.03, 1.11)	0.96 ± 0.05 (0.93, 0.99)	0.98 ± 0.06* (0.95, 1.02)	1.07 ± 0.05 (1.04, 1.10)	1.07 ± 0.05 (1.04, 1.10)	0.96 ± 0.05 (0.93, 0.99)	0.98 ± 0.05* (0.95, 1.02)	0.09	0.42	0.06	0.00	0.06	0.00	
Step Width (m)	0.06 ± 0.03 (0.05, 0.08)	0.05 ± 0.03 (0.04, 0.07)	0.05 ± 0.02 (0.04, 0.07)	0.05 ± 0.02 (0.04, 0.07)	0.07 ± 0.04 (0.04, 0.09)	0.07 ± 0.04** (0.04, 0.09)	0.06 ± 0.02 (0.05, 0.07)	0.07 ± 0.03** (0.05, 0.09)	0.19	0.18	0.19	0.48	0.40	0.21	
Walk Speed (km/h)	5.45 ± 0.17 (5.35, 5.55)	5.42 ± 0.22 (5.29, 5.55)	5.51 ± 0.00	5.51 ± 0.00	5.35 ± 0.16 (5.25, 5.44)	5.40 ± 0.12 (5.33, 5.47)	5.51 ± 0.00	5.51 ± 0.00	0.01	0.00	0.18	0.00	0.13	0.00	
Trunk															
Extension Peak Angle (°)	3.67 ± 8.89 (−9.04, 1.70)	6.29 ± 8.49 (−11.42, −1.16)	8.56 ± 4.45 (−11.38, −5.73)	12.19 ± 6.33 (−16.21, −8.17)	5.25 ± 8.03 (−10.11, −0.40)	7.87 ± 8.03 (−12.72, −3.02)	7.90 ± 5.21 (−11.21, −4.59)	11.81 ± 5.56 (−15.34, −8.28)	0.19	0.73	0.12	0.01	0.00	0.01	
Flexion Peak Angle (°)	−11.28 ± 8.47 (−16.40, −6.16)	−14.13 ± 7.87 (−18.89, −9.38)	−14.54 ± 4.79 (−17.59, −11.50)	−19.44 ± 6.08 (−23.30, −15.58)	−11.84 ± 7.14 (−16.16, −7.52)	−14.75 ± 6.67 (−18.78, −10.72)	−13.68 ± 5.62 (−17.26, −10.11)	−18.41 ± 5.87 (−22.14, −14.68)	0.83	0.84	0.02	0.02	0.00	0.00	
Pose at Heel Strike (°)	−8.52 ± 8.19 (−13.47, −3.57)	−11.55 ± 7.40 (−16.02, −7.07)	−11.83 ± 5.03 (−14.79, −8.89)	−16.77 ± 6.47 (−20.38, −12.33)	−9.24 ± 7.34 (−13.68, −4.81)	−12.19 ± 7.27 (−16.58, −7.80)	−10.65 ± 4.80 (−14.36, −7.58)	−15.60 ± 5.35 (−18.95, −11.95)	0.81	0.84	0.03	0.04	0.00	0.00	
Mean Extension/Flexion Angle (°)	−7.93 ± 8.39 (−13.00, −2.86)	−10.84 ± 7.70* (−15.49, −6.18)	−11.84 ± 4.65 (−15.03, −8.63)	−16.35 ± 6.34* (−20.88, −12.66)	−8.73 ± 7.44 (−13.23, −4.24)	−11.60 ± 7.10* (−15.89, −7.31)	−10.97 ± 5.33 (−13.70, −7.60)	−15.45 ± 5.51* (−18.99, −12.20)	0.85	0.80	0.03	0.02	0.00	0.00	
Hip															
Extension Peak Angle (°)	−15.60 ± 6.89 (−19.7, −11.43)	−17.72 ± 6.26* (−21.50, −13.94)	−13.12 ± 4.85 (−16.20, −10.04)	−15.37 ± 6.86* (−19.72, −11.01)	−16.32 ± 6.13 (−20.03, −12.62)	−18.63 ± 6.04* (−22.29, −14.98)	−12.04 ± 5.15 (−15.31, −8.77)	−15.04 ± 4.89* (−18.15, −11.94)	0.73	0.60	0.03	0.02	0.00	0.07	
Flexion Peak Angle (°)	34.00 ± 6.69 (29.96, 38.05)	33.01 ± 6.57* (29.04, 36.98)	33.85 ± 5.78 (30.18, 37.53)	33.33 ± 5.04 (30.13, 36.53)	31.86 ± 5.92 (28.28, 35.43)	30.90 ± 5.92* (27.59, 34.22)	34.53 ± 5.66 (30.93, 38.13)	33.99 ± 6.02 (30.16, 37.81)	0.41	0.10	0.16	0.02	0.00	0.00	
Pose at Heel Strike (°)	31.80 ± 6.00 (28.18, 35.42)	30.98 ± 6.01* (27.35, 34.61)	31.03 ± 5.72 (27.39, 34.66)	30.54 ± 5.63 (29.69, 34.12)	29.84 ± 5.63 (26.44, 33.24)	29.08 ± 5.89* (25.52, 32.64)	31.77 ± 5.79 (28.09, 35.45)	31.61 ± 7.40 (29.61, 36.32)	0.35	0.03	0.14	0.03	0.00	0.02	
Adduction Peak Angle (°)	−17.26 ± 4.41 (−19.9, −14.60)	−16.94 ± 4.15 (−19.6, −14.30)	−15.31 ± 2.43 (−16.85, −13.76)	−17.65 ± 3.12* (−19.63, −15.67)	−17.33 ± 4.41 (−20.0, −14.70)	−18.33 ± 4.83 (−21.0, −15.70)	−16.37 ± 2.83 (−18.16, −14.57)	−19.01 ± 2.58* (−20.65, −17.37)	0.08	0.83	0.02	0.17	0.08	0.05	
Abduction Peak Angle (°)	11.85 ± 2.80 (10.50, 13.20)	12.87 ± 2.18 (11.50, 14.60)	12.51 ± 1.74 (11.41, 13.62)	13.65 ± 2.16* (12.28, 15.02)	12.90 ± 2.03 (9.66, 12.40)	11.15 ± 2.36 (9.80, 12.50)	12.53 ± 2.86 (10.72, 14.35)	13.40 ± 3.36* (11.26, 15.53)	0.05	0.40	0.00	0.00	0.15	0.03	
Internal Rotation Peak Angle (°)	−18.00 ± 5.73 (−21.90, −14.10)	−17.41 ± 6.23 (−21.30, −13.50)	−15.68 ± 6.23 (−19.64, −11.72)	−17.31 ± 6.60* (−21.50, −13.12)	−18.14 ± 6.46 (−21.60, −13.70)	−17.65 ± 8.05 (−22.10, −14.20)	−15.04 ± 5.26 (−18.38, −11.72)	−16.72 ± 6.52* (−20.87, 12.58)	0.00	0.50	0.00	0.02	0.00	0.00	

(continued)

TABLE I. (Continued)

	Pre-training				Post-training				ES (η_p^2)					
	Male		Female		Male		Female		Distance marched		Training		Interaction	
	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march						
Variable	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Male	Female	Male	Female	Male	Female
External Rotation Peak Angle (°)	7.99 ± 5.84 (4.07, 11.90)	9.72 ± 7.75 (5.80, 13.60)	9.04 ± 5.66 (5.45, 12.64)	9.89 ± 4.94 (6.75, 13.02)	7.00 ± 6.55 (3.08, 10.90)	7.51 ± 6.95 (3.59, 11.40)	8.68 ± 5.00 (5.50, 11.86)	9.63 ± 5.27 (6.28, 12.99)	0.08	0.30	0.00	0.01	0.08	0.00
Excursion (°)	49.94 ± 4.13 (46.74, 52.34)	51.03 ± 3.49 (48.59, 53.11)	46.97 ± 4.10 (44.36, 49.58)	48.70 ± 6.12* (44.81, 52.59)	47.84 ± 4.21 (45.98, 50.64)	49.22 ± 4.00 (47.16, 51.910)	46.57 ± 5.26 (43.23, 49.91)	49.03 ± 4.71* (46.04, 52.02)	0.59	0.40	0.15	0.00	0.00	0.03
Knee														
Extension Peak Angle (°)	−1.96 ± 2.94 (−0.18, −3.74)	−1.55 ± 3.24 (−0.41, 3.50)	−7.53 ± 2.88 (−5.71, 9.36)	−6.87 ± 3.74 (−4.50, 9.25)	−0.90 ± 2.82 (−0.81, 2.60)	−0.53 ± 2.7 (−1.13, 2.18)	−6.75 ± 4.71 (−3.76, −9.74)	−5.81 ± 4.87 (−2.71, −8.90)	0.25	0.24	0.20	0.06	0.00	0.03
First Flexion Peak Angle (°)	24.51 ± 5.12 (21.42, 27.60)	25.66 ± 5.62* (22.26, 29.05)	23.15 ± 4.22 (20.47, 25.83)	23.86 ± 4.41 (21.06, 26.66)	27.06 ± 13.99 (19.15, 36.06)	28.59 ± 14.40* (19.89, 37.30)	21.93 ± 5.07 (18.71, 25.15)	23.16 ± 6.34 (19.13, 27.19)	0.36	0.24	0.07	0.06	0.03	0.04
Second Flexion Peak Angle (°)	71.53 ± 5.51 (68.20, 74.86)	72.59 ± 4.75* (69.72, 75.46)	68.20 ± 3.19 (66.17, 70.22)	69.99 ± 2.83* (68.19, 71.78)	71.21 ± 3.68 (68.99, 73.43)	72.40 ± 4.11* (69.91, 74.88)	67.96 ± 3.36 (65.83, 70.10)	68.57 ± 2.11*,*** (67.23, 69.91)	0.14	0.40	0.00	0.11	0.00	0.38
Pose at Heel Strike (°)	7.82 ± 3.41 (5.77, 9.88)	9.05 ± 4.35* (6.42, 11.67)	16.20 ± 3.51 (13.96, 18.43)	17.08 ± 4.01 (14.53, 19.63)	7.06 ± 2.64 (5.47, 8.66)	7.40 ± 2.91* (5.65, 9.16)	15.72 ± 4.42 (12.92, 18.53)	16.60 ± 5.17 (13.31, 19.88)	0.29	0.23	0.16	0.03	0.09	0.00
Internal Rotation Peak Angle (°)	−0.16 ± 0.08 (−0.19, −0.12)	0.14 ± 0.06 (−0.18, −0.10)	−0.09 ± 0.09 (−0.15, −0.03)	0.13 ± 0.09* (−0.19, −0.07)	−0.14 ± 0.08 (−0.17, −0.96)	−0.12 ± 0.06 (−0.16, −0.08)	−0.09 ± 0.07 (−0.14, −0.05)	−0.14 ± 0.07* (−0.19, −0.09)	0.08	0.36	0.00	0.02	0.00	0.02
External Rotation Peak Angle (°)	0.12 ± 0.08 (0.07, 0.17)	0.12 ± 0.10 (0.07, 0.18)	0.11 ± 0.08 (0.06, 0.16)	0.13 ± 0.10 (0.06, 0.19)	0.12 ± 0.09 (0.07, 0.17)	0.13 ± 0.09 (0.08, 0.18)	0.11 ± 0.06 (0.07, 0.15)	0.12 ± 0.09 (0.07, 0.18)	0.00	0.01	0.00	0.00	0.00	0.00
Excursion (°)	74.68 ± 6.37 (71.28, 78.73)	75.92 ± 5.89 (72.29, 79.40)	75.73 ± 4.30 (73.00, 78.46)	76.86 ± 4.93 (73.73, 79.99)	73.70 ± 5.15 (70.34, 76.59)	73.99 ± 4.83 (71.07, 76.93)	74.75 ± 5.62 (71.18, 78.32)	74.43 ± 5.06 (71.21, 77.64)	0.23	0.04	0.14	0.08	0.01	0.26
Ankle														
Dorsiflexion Peak Angle (°)	8.34 ± 2.94 (6.56, 10.11)	7.19 ± 2.44 (5.71, 8.67)	7.26 ± 2.46 (5.70, 8.82)	7.22 ± 2.70 (5.50, 8.93)	9.15 ± 2.23 (7.81, 10.50)	9.13 ± 1.98** (7.94, 10.33)	8.43 ± 2.07 (7.12, 9.75)	8.66 ± 2.46 (7.09, 10.23)	0.18	0.01	0.52	0.26	0.09	0.03
Plantarflexion Peak Angle (°)	−21.74 ± −7.41 (−26.22, −17.6)	−23.38 ± 5.42 (−26.65, −20.10)	−12.05 ± 3.44 (−14.69, −10.32)	−13.68 ± 4.55* (−16.57, −10.79)	−21.65 ± 5.87 (−25.19, −18.10)	−22.21 ± 5.88 (−25.77, −18.66)	−12.05 ± 2.70 (−13.77, −10.34)	−12.89 ± 3.35 (−15.02, −10.76)	0.07	0.31	0.10	0.07	0.08	0.04
Pose at Heel Strike (°)	1.17 ± 3.68 (−1.06, 3.40)	0.08 ± 3.45 (−2.01, 2.16)	−3.57 ± 3.16 (−5.58, −1.56)	−4.31 ± 3.10 (−6.27, −2.34)	1.42 ± 3.02 (−0.40, 3.24)	1.46 ± 3.00 –0.36, 3.27)	−2.33 ± 2.60 (−3.99, −0.68)	−2.67 ± 2.26 (−4.11, −1.24)	0.08	0.23	0.18	0.30	0.08	0.07
Excursion (°)	30.18 ± 6.08 (26.28, 33.73)	32.19 ± 6.33 (28.33, 35.98)	19.76 ± 2.29 (18.31, 21.22)	20.89 ± 3.50 (18.67, 23.12)	30.70 ± 4.83 (28.12, 33.73)	31.38 ± 4.76 (28.44, 34.33)	20.49 ± 2.33 (19.01, 21.97)	21.55 ± 3.10 (19.58, 23.52)	0.15	0.29	0.00	0.20	0.08	0.00

Direct statistical comparisons were not conducted between male and female data presented.

Abbreviations: 95% CI = 95% confidence interval. ES(η_p^2) = effect size (partial eta-squared).

*Indicates significant ($P < .05$) main effect of distance marched.

**Indicates significant ($P < .05$) main effect of training.

***Indicates significant ($P < .05$) distance march by training interaction.

TABLE II. Mean ± Standard Deviation Magnitudes for External Joint Moments (N·m/kg^{-1}), Power (W·kg^{-1}), and Work (J·kg^{-1}) Variables

Variable	Pre-training				Post-training				ES (η_p^2)					
	Male		Female		Male		Female		Distance marched		Training		Interaction	
	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march						
	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Male	Female	Male	Female	Male	Female
Hip														
Extension Moment	−2.12 ± 0.34 (−2.33, −1.92)	−2.30 ± 0.33* (−2.50, −2.10)	−1.24 ± 0.34 (−1.02, −1.46)	−1.45 ± 0.50* (−1.14, 1.77)	−2.00 ± 0.32 (−2.19, −1.81)	−2.18 ± 0.31* (−2.36, −1.99)	−1.35 ± 0.21 (−1.22, −1.49)	−1.52 ± 0.22* (−0.38, 1.66)	0.75	0.38	0.17	0.07	0.00	0.02
Flexion Moment	1.37 ± 0.39 (1.13, 1.60)	1.33 ± 0.35 (1.12, 1.55)	1.45 ± 0.33 (1.66, 1.21)	1.60 ± 0.47 (1.90, 1.30)	1.43 ± 0.39 (1.19, 1.67)	1.47 ± 0.46 (1.19, 1.74)	1.58 ± 0.28 (1.76, 1.40)	1.60 ± 0.43 (1.87, 1.33)	0.00	0.08	0.08	0.02	0.13	0.06
Positive Hip Power	0.67 ± 0.13 (0.59, 0.75)	0.70 ± 0.10 (0.64, 0.76)	0.71 ± 0.22 (0.57, 0.85)	0.85 ± 0.33* (0.64, 1.06)	0.60 ± 0.12 (0.53, 0.68)	0.63 ± 0.10 (0.56, 0.69)	0.74 ± 0.22 (0.60, 0.88)	0.89 ± 0.29 (0.70, 1.07)	0.21	0.41	0.20	0.00	0.01	0.00
Negative Hip Power	−0.82 ± 0.15 (−0.91, −0.73)	−0.83 ± 0.20 (−0.95, −0.71)	−0.12 ± 0.05 (−0.15, −0.08)	−0.13 ± 0.07 (−0.17, −0.09)	−0.81 ± 0.18 (−0.92, −0.71)	−0.79 ± 0.16 (−0.89, −0.69)	−0.12 ± 0.04 (−0.14, −0.09)	−0.13 ± 0.06 (−0.17, −0.09)	0.01	0.07	0.08	0.02	0.05	0.00
Joint Work Positive	0.35 ± 0.07 (0.31, 0.40)	0.37 ± 0.05 (0.34, 0.41)	0.34 ± 0.10 (0.27, 0.41)	0.42 ± 0.16* (0.31, 0.52)	0.32 ± 0.06 (0.28, 0.36)	0.33 ± 0.05 (0.30, 0.36)	0.36 ± 0.10 (0.29, 0.42)	0.43 ± 0.13 (0.35, 0.52)	0.35	0.48	0.19	0.02	0.02	0.00
Joint Work Negative	−0.14 ± 0.06 (−0.17, −0.10)	−0.13 ± 0.04 (−0.16, −0.11)	−0.06 ± 0.02 (−0.07, −0.04)	−0.06 ± 0.03 (−0.09, −0.04)	−0.14 ± 0.05 (−0.18, −0.11)	−0.15 ± 0.06 (−0.19, −0.11)	−0.06 ± 0.02 (−0.07, −0.05)	−0.06 ± 0.03 (−0.08, −0.04)	0.00	0.10	0.04	0.00	0.04	0.00
Net Joint Work	0.22 ± 0.11 (0.16, 0.29)	0.24 ± 0.08 (0.19, 0.29)	0.28 ± 0.11 (0.21, 0.35)	0.35 ± 0.15* (0.26, 0.45)	0.18 ± 0.07 (0.14, 0.22)	0.19 ± 0.07 (0.15, 0.23)	0.30 ± 0.09 (0.29, 0.42)	0.37 ± 0.14 (0.35, 0.52)	0.16	0.45	0.14	0.02	0.06	0.00
Knee														
Extension Moment (First Peak)	−0.83 ± 0.18 (−0.73, −0.94)	−0.84 ± 0.24 (−0.70, −0.99)	−0.33 ± 0.39 (−0.09, −0.59)	−0.25 ± 0.31 (−0.06, −0.45)	−0.74 ± 0.14 (−0.66, −0.83)	−0.80 ± 0.14 (−0.71, 0.88)	−0.16 ± 0.08 (−0.11, −0.21)	−0.20 ± 0.29** (−0.01, −0.38)	0.25	0.04	0.28	0.23	0.05	0.00
Extension Moment (Second Peak)	−1.04 ± 0.26 (−0.88, −1.19)	−1.10 ± 0.26* (−0.95, −1.26)	−0.29 ± 0.30 (−0.10, −0.48)	−0.35 ± 0.37 (−0.12, −0.59)	−0.97 ± 0.17 (−0.86, −1.07)	−1.05 ± 0.21* (−0.93, −1.18)	−0.27 ± 0.29 (−0.09, −0.46)	−0.33 ± 0.34 (−0.11, −0.55)	0.48	0.24	0.11	0.07	0.01	0.00
Flexion Moment (First Peak)	2.30 ± 0.60 (2.67, 1.94)	2.36 ± 0.64 (2.75, 1.97)	0.26 ± 0.28 (0.44, 0.09)	0.35 ± 0.39* (0.59, 0.10)	2.31 ± 0.58 (2.66, 1.96)	2.33 ± 0.56 (2.66, 1.99)	0.31 ± 0.34 (0.53, 0.10)	0.39 ± 0.43 (0.67, 0.12)	0.03	0.36	0.00	0.13	0.01	0.00
Flexion Moment (Second Peak)	0.34 ± 0.11 (0.41, 0.28)	0.32 ± 0.12 (0.39, 0.25)	0.25 ± 0.27 (0.42, 0.08)	0.35 ± 0.41* (0.61, 0.09)	0.34 ± 0.12 (0.41, 0.27)	0.32 ± 0.12 (0.39, 0.25)	0.25 ± 0.30 (0.44, 0.07)	0.35 ± 0.40 (0.61, 0.09)	0.19	0.32	0.00	0.00	0.00	0.00
Positive Knee Power	0.39 ± 0.09 (0.33, 0.44)	0.44 ± 0.16 (0.34, 0.54)	0.10 ± 0.05 (0.06, 0.13)	0.08 ± 0.03* (0.06, 0.10)	0.37 ± 0.08 (0.32, 0.41)	0.40 ± 0.11 (0.33, 0.46)	0.09 ± 0.04 (0.07, 0.11)	0.09 ± 0.05 (0.06, 0.12)	0.21	0.10	0.25	0.00	0.06	0.09
Negative Knee Power	−0.82 ± 0.15 (−0.91, −0.73)	−0.83 ± 0.20 (−0.95, −0.71)	−0.53 ± 0.15 (−0.62, −0.44)	−0.61 ± 0.19 (−0.74, −0.49)	−0.81 ± 0.18 (−0.92, −0.71)	−0.79 ± 0.16 (−0.89, −0.69)	−0.54 ± 0.13 (−0.62, −0.46)	−0.63 ± 0.20 (−0.76, −0.50)	0.01	0.39	0.08	0.01	0.05	0.00
Positive Joint Work	0.21 ± 0.05 (0.18, 0.24)	0.23 ± 0.08 (0.19, 0.28)	0.05 ± 0.03 (0.03, 0.06)	0.04 ± 0.01 (0.03, 0.05)	0.20 ± 0.04 (0.17, 0.22)	0.21 ± 0.05 (0.18, 0.24)	0.04 ± 0.02 (0.03, 0.05)	0.04 ± 0.02 (0.03, 0.06)	0.22	0.07	0.21	0.00	0.08	0.08
Negative Joint Work	−0.43 ± 0.07 (−0.48, −0.39)	−0.44 ± 0.09 (−0.49, −0.39)	−0.25 ± 0.07 (−0.30, −0.21)	−0.30 ± 0.10* (−0.36, −0.24)	−0.43 ± 0.08 (−0.48, −0.38)	−0.42 ± 0.08 (−0.47, −0.38)	−0.26 ± 0.06 (−0.30, −0.22)	−0.31 ± 0.10 (−0.37, −0.24)	0.01	0.47	0.06	0.01	0.06	0.00

(continued)

TABLE II. (Continued)

	Pre-training				Post-training				ES (η_p^2)					
	Male		Female		Male		Female		Distance marched		Training		Interaction	
	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march	Pre-march	Post-march						
Variable	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Mean ± SD 95% CI (lower, upper)	Male	Female	Male	Female	Male	Female
Net Joint Work	0.22 ± 0.11 (0.16, 0.29)	0.24 ± 0.08 (0.19, 0.29)	0.21 ± 0.07 (0.25, 0.16)	0.26 ± 0.09* (0.32, 0.21)	0.18 ± 0.07 (0.14, 0.22)	0.19 ± 0.07 (0.15, 0.23)	0.21 ± 0.06 (0.25, 0.18)	0.26 ± 0.09 (0.32, 0.20)	0.16	0.53	0.14	0.01	0.06	0.01
Ankle														
Dorsiflexion Moment	0.50 ± 0.06 (0.46, 0.54)	0.45 ± 0.12 (0.38, 0.53)	0.45 ± 0.56 (0.1., 0.81)	0.38 ± 0.44 (0.10, 0.66)	0.48 ± 0.10 (0.42, 0.54)	0.47 ± 0.10 (0.41, 0.53)	0.14 ± 0.08 (0.09, 0.19)	0.15 ± 0.06 (0.11, 0.18)	0.09	0.03	0.00	0.30	0.09	0.04
Plantarflexion Moment	−4.10 ± 0.19 (−4.21, −3.98)	−4.03 ± 0.22 (−4.16, −3.89)	−1.76 ± 0.61 (−2.15, −1.38)	−1.81 ± 0.64 (−2.21, −1.40)	−4.08 ± 0.21 (−4.20, −3.95)	−4.09 ± 0.23 (−4.23, −3.96)	−1.83 ± 0.60 (−2.22, −1.45)	−1.87 ± 0.63 (−2.27, −1.47)	0.05	0.05	0.03	0.12	0.24	0.00
Positive Ankle Power	0.79 ± 0.09 (0.73, 0.84)	0.75 ± 0.11 (0.69, 0.82)	0.37 ± 0.15 (0.27, 0.46)	0.32 ± 0.13* (0.24, 0.40)	0.78 ± 0.09 (0.73, 0.84)	0.79 ± 0.13 (0.71, 0.87)	0.38 ± 0.14 (0.29, 0.46)	0.36 ± 0.14** (0.27, 0.45)	0.02	0.40	0.06	0.30	0.08	0.10
Negative Ankle Power	−0.30 ± 0.13 (−0.38, −0.22)	−0.28 ± 0.09 (−0.33, −0.23)	−0.11 ± 0.05 (−0.14, −0.08)	−0.14 ± 0.07 (−0.17, −0.10)	−0.33 ± 0.13 (−0.41, −0.26)	−0.33 ± 0.08 (−0.38, −0.29)	−0.12 ± 0.06 (−0.16, −0.08)	−0.14 ± 0.08 (−0.19, −0.09)	0.03	0.38	0.55	0.01	0.10	0.04
Positive Joint Work	0.42 ± 0.05 (0.39, 0.44)	0.40 ± 0.05 (0.37, 0.43)	0.18 ± 0.07 (0.13, 0.22)	0.16 ± 0.07 (0.12, 0.20)	0.42 ± 0.04 (0.39, 0.44)	0.42 ± 0.06 (0.39, 0.46)	0.18 ± 0.07 (0.14, 0.22)	0.18 ± 0.07 (0.13, 0.22)	0.00	0.23	0.06	0.29	0.09	0.09
Negative Joint Work	−0.43 ± 0.07 (−0.48, −0.39)	−0.44 ± 0.09 (−0.49, −0.39)	−0.05 ± 0.02 (−0.07, −0.04)	−0.07 ± 0.03* (−0.09, −0.05)	−0.43 ± 0.08 (−0.48, −0.38)	−0.42 ± 0.08 (−0.47, −0.38)	−0.06 ± 0.03 (−0.08, −0.04)	−0.07 ± 0.04 (−0.09, −0.04)	0.01	0.43	0.06	0.01	0.06	0.05
Net Joint Work	0.26 ± 0.10 (0.19, 0.32)	0.25 ± 0.09 (0.20, 0.30)	0.12 ± 0.06 (0.09, 0.16)	0.09 ± 0.05* (0.06, 0.12)	0.24 ± 0.09 (0.18, 0.29)	0.24 ± 0.07 (0.20, 0.29)	0.12 ± 0.05 (0.09, 0.16)	0.11 ± 0.06 (0.07, 0.14)	0.00	0.58	0.08	0.11	0.01	0.18
Net														
Positive Power Total	1.84 ± 0.15 (1.75, 1.93)	1.90 ± 0.25 (1.75, 2.05)	1.18 ± 0.34 (0.96, 1.39)	1.25 ± 0.40 (0.99, 1.50)	1.75 ± 0.18 (1.64, 1.86)	1.81 ± 0.23 (1.68, 1.95)	1.21 ± 0.32 (1.01, 1.41)	1.33 ± 0.39 (1.08, 1.58)	0.15	0.19	0.26	0.05	0.00	0.06
Negative Power Total	−1.38 ± 0.17 (−1.48, −1.27)	−1.36 ± 0.21 (−1.49, −1.23)	−0.76 ± 0.21 (−0.89, −0.62)	−0.88 ± 0.28 (−1.06, −0.71)	−1.41 ± 0.18 (−1.52, −1.30)	−1.40 ± 0.18 (−1.51, −1.29)	−0.77 ± 0.19 (−0.89, −0.65)	−0.89 ± 0.23 (−1.04, −0.75)	0.03	0.45	0.10	0.01	0.00	0.00
Positive Work Total	0.98 ± 0.07 (0.94, 1.02)	1.01 ± 0.09 (0.96, 1.06)	0.56 ± 0.16 (0.46, 0.67)	0.61 ± 0.20 (0.48, 0.74)	0.93 ± 0.07 (0.89, 0.98)	0.97 ± 0.10 (0.91, 1.03)	0.58 ± 0.15 (0.48, 0.67)	0.65 ± 0.18 (0.53, 0.77)	0.23	0.28	0.22	0.04	0.00	0.04
Negative Work Total	−0.73 ± 0.08 (−0.78, −0.68)	−0.72 ± 0.08 (−0.77, −0.67)	−0.36 ± 0.10 (−0.42, −0.30)	−0.43 ± 0.14 (−0.52, −0.35)	−0.75 ± 0.09 (−0.81, −0.70)	−0.75 ± 0.09 (−0.81, −0.69)	−0.37 ± 0.09 (−0.43, −0.31)	−0.44 ± 0.11* (−0.51, −0.37)	0.02	0.53	0.15	0.01	0.00	0.04

Direct statistical comparisons were not conducted between male and female data presented.
Abbreviations: 95% CI, 95% confidence interval; ES(η_p^2), effect size (partial eta-squared).
*Indicates significant ($P < .05$) main effect of distance marched.
**Indicates significant ($P < .05$) main effect of training.
***Indicates significant ($P < .05$) distance march by training interaction.

was found for second flexion peak angle at the knee joint ($P = .025$, $\eta_p^2 = 0.38$), as the change in peak flexion was greater at the post-march measure before training compared to after training (2.6% vs. 0.9% increase, respectively). In the frontal plane, peak joint angles for hip adduction ($P = .00$, $\eta_p^2 = 0.825$), abduction ($P = .021$, $\eta_p^2 = 0.40$), and excursion ($P = .025$, $\eta_p^2 = 0.38$) significantly increased over the distance marched. Increases were further observed in the transverse plane for peak hip ($P = .07$, $\eta_p^2 = 0.50$) and knee joint internal rotation ($P = .031$, $\eta_p^2 = 0.36$) kinematic variables. No main effects of training were observed for hip, knee, or ankle kinematics.

Joint Moments, Power, and Work

Males demonstrated significant increases in peak hip extension ($P < .05$, $\eta_p^2 = 0.75$) and second peak moment knee extension ($P < .05$, $\eta_p^2 = 0.48$) joint moments over the distance marched (Table II). Percentage contribution of the hip to total positive power also increased over the distance marched, whereas ankle joint contribution toward total positive power significantly decreased ($P < .05$, $\eta_p^2 = 0.35$) (Fig. 2). The main effects of training were found at the initial contact of the stance phase (0–40%) for the first peak knee extension moment ($P < .05$, $\eta_p^2 = 0.28$) where values significantly increased from pre- to post-march after training compared to before training (Fig. 1). Furthermore, a main effect of training was shown for the percentage contribution of total negative knee power, which increased before training but was maintained from pre-to-post march after training ($P < .05$, $\eta_p^2 = 0.44$) (Fig. 2). At the ankle after training, the percentage contribution toward total positive power was significantly larger at the post-march measurement compared to before march measurement (43.6% vs. 39.9% contribution, respectively). Negative ankle power was maintained from pre- to post-march measures after training compared to before training where negative power reduced ($P < .05$, $\eta_p^2 = 0.55$). There were no main effects of or significant interactions between the distance marched or training found for joint work variables.

Females demonstrated a main effect of distance marched for sagittal plane joint moment variables at the hip and knee (Table II). Specifically, significant increases in peak hip extension ($P = .025$, $\eta_p^2 = 0.38$), the first knee flexion peak during the stance phase (0–40%) ($P = .030$, $\eta_p^2 = 0.36$), and the second knee flexion peak during the swing phase ($P = .045$, $\eta_p^2 = 0.32$) were found (Fig. 1). Percentage contribution of the hip toward positive power increased over the distance marched ($P = .001$, $\eta_p^2 = 0.64$), whereas knee ($P = .038$, $\eta_p^2 = 0.33$) and ankle ($P = .001$, $\eta_p^2 = 0.63$) contributions decreased (Fig. 2). At the hip, net joint work completed increased over the distance marched ($P = .012$, $\eta_p^2 = 0.45$), primarily through greater positive work done ($P = .009$, $\eta_p^2 = 0.48$). Similar increases in net work were observed at the knee ($P = .005$, $\eta_p^2 = 0.53$) and ankle ($P = .002$, $\eta_p^2 = 0.58$)

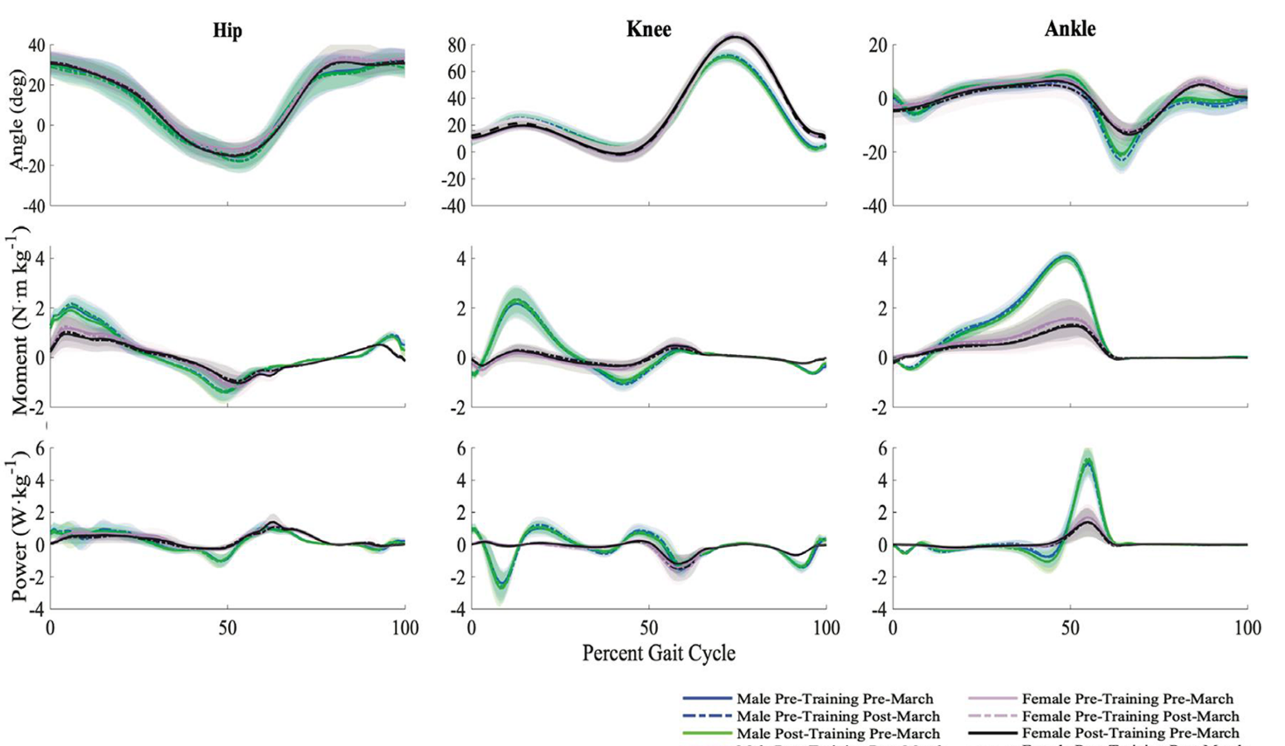

FIGURE 1. Mean (lines) and standard deviation (shaded regions) for joint angles, moments, and powers for the hip, knee, and ankle joints over the 5 km distance marched. Male and female data are presented during the load carriage task before and after the 10-week physical training intervention, respectively.

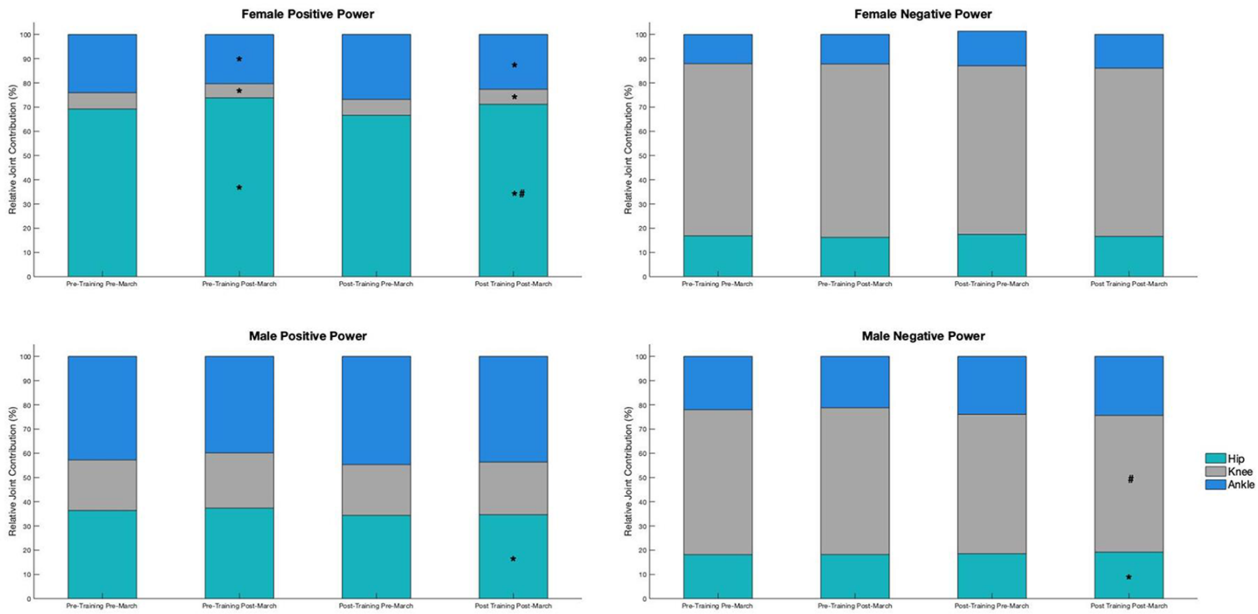

FIGURE 2. Relative contributions of hip, knee, and ankle joints to total mechanical positive and negative power during stance over the 5 km distance marched. Male and female data are presented during the load carriage task (pre-march; 0 km, and post-march; 5 km) before and after the 10-week physical training intervention, respectively. *Indicates significant ($P < .05$) main effect of distance marched. #Indicates significant ($P < .05$) main effect of training.

over the distance marched; however, increases in negative work at the knee ($P = .010$, $\eta_p^2 = 0.47$) and ankle ($P = .015$, $\eta_p^2 = 0.43$) contributed toward these changes. At the ankle, a main effect of training was found as positive power decreased by 13.5% from pre- to post-march before training, but it remained unchanged after training ($P = .05$, $\eta_p^2 = 0.29$). Total negative work completed during the load carriage march was greater over the distance marched ($P = .005$, $\eta_p^2 = 0.53$). No interactions between the distance marched and training were observed for females.

DISCUSSION

The purpose of this study was to determine sex-specific adaptations in lower limb biomechanics during a standardized load carriage task and in response to a 10-week evidence-based physical training program. Although direct statistical comparisons will not be made between males and females due to the differences in data acquisition methods, it is still important to consider how results are comparable between the sexes qualitatively. Consistent with our hypotheses, lower limb kinematic and kinetic responses differed between males and females over the 5 km load carriage task and after training. Adaptive responses in gait variables were primarily observed at the hip and knee joints for females and at the knee and ankle joints for males. In contrast to our second hypothesis, we found that knee joint moments increased for both sexes over the 5 km march. Our final hypothesis stated that lower limb net joint powers would be maintained over the distance marched after training compared to before training. Interestingly, training resulted in a maintenance of ankle power in males only. To the authors' knowledge, this study is the first to identify sex-specific lower limb adaptations in response to load carriage and a tailored physical training program.

Training elicited similar adaptive responses in spatiotemporal variables for both sexes. Step width increased for both sexes during the loaded march after training to increase stability through a wider base of support.[6,28] Surprisingly, in the current study female participants increased their stride length during the loaded march, which is in contrast to previously reported findings. Load carriage tasks require females to shorten their strides and increase stride frequency to maintain stability and attenuate load-induced external torques.[7,28] It may be that females were not able to increase or maintain an increased stride frequency in order to maintain the prescribed 5.5 km·h^{-1} marching pace for 55-min, resulting in the increased stride length. Although this is a seemingly effective gait strategy to meet pace, it often requires an individual to take longer steps relative to their body height.[29] This overstriding can place additional shearing stress on the pelvis, leading to stress reactions or stress fractures in the pelvic bones.[30] Injuries of this nature are common among female military recruits[30] and pose a significant challenge to military organizations when integrating female soldiers into combat roles. The physical demands of combat-related occupations require load carriage tasks to be standardized, meaning that other prevention strategies specific to females need to be further considered. In agreement with Krupenevich et al.,[7] females exhibited greater time-course changes in trunk flexion compared to males (4.5° vs. 2.9°, respectively) when carrying the 23 kg load. Combined with the observed changes in stride, these findings suggest females adapt their gait mechanics during standardized load carriage to account for their smaller body mass and the additional hip flexion and knee extension moments experienced.[31,32] Adopting this gait strategy may reduce female soldiers' task tolerance or capability to complete heavy prolonged load carriage tasks, especially as these evoke greater gait alterations in comparison to shorter tasks.[4]

Supporting our first hypothesis, hip and knee joint kinematic and kinetic responses differed between sexes. Over the distance marched, females demonstrated changes in frontal plane kinematics at the hip joint (adduction, abduction, and excursion peak angles) and in transverse plane kinematics at the hip and knee joint (internal rotation peak angle). These findings contrast with the work by Loverro et al.,[10] who observed changes in hip kinematics for males only walking on a treadmill. Variations in movement patterns between sexes could be explained by known structural differences, particularly at the hips and knees. For example, females exhibit a greater Q angle (i.e., hip width to femoral length ratio) and natural internal hip rotation angle compared to males.[33,34] Differences revealed in hip and knee gait adaptation strategies between sexes in response to load may contribute to the higher incidence of lower limb injuries seen in female soldiers.[10] Interestingly, similar joint responses for females were not evident after training, suggesting that females developed an increased capacity to control movement during the dynamic load carriage task. Males demonstrated a similar response after training, as hip moments remained stable suggesting that training did not impair normal hip biomechanics. Combined, these findings indicate that the stimulus provided by the 10-week lower limb focused training was sufficient enough to elicit enhanced limb coordination and control in females, while maintaining the efficiency of movement patterns in males during the load carriage task.

Consistent with prior research, hip and knee joint extensor moments increased over the 5 km load carriage task for both sexes.[35–37] Females experienced increased knee flexion moments during both stance (0-40%) and swing phases of gait, which may increase the amount of cumulative loading experienced at the knee joint.[32] In comparison, males experienced increased knee extension moments during the stance phase and an increased knee flexion angle at heel strike. Together, a pre-stretch of the knee extensors likely occurred, increasing the quadriceps extension moment arm and resulting in an increased knee extensor moment for a given muscle activation.[37] Further, increases in knee extensor moments during early stance actively control the descent of the added load and to counteract center of mass excursions subsequently experienced.[37] Confirming our second hypothesis, males demonstrated a significant reduction in peak knee joint extension moments at the initial contact gait (0–40% stance) after training. We anticipate that the minimized knee joint moments experienced during the load carriage task are due to improvements in lower limb strength elicited by the 10 weeks of targeted training. Individuals who lack knee extensor strength are known to be at greater risk of lower limb MSI, as quadriceps muscle activity significantly increases during the loading response phase of gait.[8] Minimizing knee joint moments through improving strength may in turn help minimize the risk of MSI in male soldiers. However, it appears that this conclusion cannot be applied to a female population. There was no difference in knee extension moments after completing the same standardized training, but the amount of negative work produced at the knee joint increased. During load carriage, the knee performs proportionally increasing negative work, to attenuate increased forces experienced at ground contact.[37] The increased reliance on knee muscles could precipitate fatigue during loaded walking[35] and expose military personnel to increased risk of overuse MSI. Therefore, an alternative strategy for females may be required to elicit the same benefits of training that are transferable to load carriage tasks.

Although both sexes successfully maintained negative ankle joint powers over the 5 km load carriage task after training compared to before training, different strategies were adopted in response to training. A distal shift of positive power production toward the ankle suggests that males adopted an ankle-driven strategy,[8,35] whereas females generated greater hip power after training suggesting they adopted a more hip-dominant strategy. Indeed, shifting relative joint power contributions distally is an efficient strategy to assist with forward progression when carrying evenly distributed load configurations, as increased ankle push-off propels the COM (centre of mass) forward and upward.[36] However, shifting task requirements proximally would actively decrease reliance on knee musculature to produce positive work/power,[31,32] potentially decreasing injury risks at one of the most commonly injured sites in military personnel. Given the primary focus of the 10-week training intervention was on the lower limb musculature (specifically focused on the hip extensor and flexor muscles), the variations in adaptive gait strategies adopted by males and females are surprising. These findings are the first to detect sex differences in response to a standardized military-relevant load carriage task and to specific training. As such, further work is required to quantify and statistically compare males and females during load carriage.

The current study has some limitations that should be acknowledged. Kinetic data for males and females were acquired using over-ground and treadmill-based protocols; therefore, direct statistical comparisons were not conducted. However, previous research has demonstrated comparable lower limb kinetic data when collected using these different acquisition methods.[38,39] Therefore, the authors feel that the conclusions drawn based on the results presented for males and females are comparable. Knee flexion and extension DOFs were used to determine non-sagittal knee joint motions (abduction/adduction, internal/external rotations, as well as tibial translations) using the same base functions, which were then scaled for each subject. This method was chosen as secondary knee motion measures taken from skin-surface marker data are error prone.[40] The participants recruited were recreationally active civilians but were representative of a recruit military population as they met inclusion criteria used by the Australian Army, meaning the applicability of current findings may be limited to initial recruits as opposed to experienced soldiers.

In conclusion, this study identified sex-specific lower limb biomechanical differences in response to a standardized, military-relevant load carriage task and to specific training. Primary differences were realized at the hip joint for females and the ankle for males, suggesting that physical training should be tailored to meet the requirements of each sex to maximize adaptive benefits relevant to load carriage tasks. Future work should look to modifying the current training program and implementing specific elements (i.e., more load carriage–specific conditioning) to address areas of concern to improve female soldiers' load-carrying capabilities. This will not only enhance understanding in this area but will also develop a strong evidence base to inform military organizations and facilitate the successful integration of female soldiers into physically demanding combat roles.

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SUPPLEMENTARY MATERIAL

Supplementary material is available at *Military Medicine* online.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest that could bias this research, including financial and/or personal relationships with other people or organizations.

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