Original Research

Examining Planar Contributions to Knee Total Joint Moment Between Women and Men During Loaded Gait Tasks

Kellen T. Krajewski,[*†‡] PhD, Camille C. Johnson,[§] PhD, Qi Mi,[†] PhD, Shawn D. Flanagan,[†||] PhD, William J. Anderst,[§] PhD, and Christopher Connaboy,[†||] PhD
Investigation performed at the University of Pittsburgh, Pittsburg, Pennsylvania, USA

Background: Military personnel in combat roles observe a high prevalence of knee osteoarthritis. Knee total joint moment (KTJM) and the knee adduction moment percentage contribution (KAM%) of KTJM have been linked to knee osteoarthritis. It is postulated that sex, load carriage, and imposed locomotion patterns such as forced marching (FM) alter mechanics of the knee. The purpose of this study was to determine the effects of ''military-relevant'' load magnitudes, locomotion patterns, and sex on KTJM and its planar percentage contributions in recruit-aged adults during short-duration gait tasks.

Hypothesis: The greatest load magnitude and FM will significantly increase KAM contribution to KTJM compared with lower magnitudes or no load. Additionally, women will exhibit greater KAM contribution to KTJM compared with men regardless of experimental condition.

Study Design: Controlled laboratory study.

Methods: Twenty healthy recruit-aged (18-35 years) adults (10 male, 10 female) executed trials of running and FM with no load (BW), an additional load of 45% of BW, and an additional load of 55% of BW. KTJM was calculated along with each plane of motion percentage contribution: knee flexion moment (KFM%), KAM%, and knee rotation moment (KRM%). A $3 \times 2 \times 2$ mixed model analysis of variance was used to evaluate the effects of load carriage, locomotion pattern, and sex on KTJM, KFM%, KAM%, and KRM% at multiple gait events of stance phase.

Results: FM exhibited a greater ($P < .001$) KTJM than running at heel strike. Running had greater KAM% ($P = .01$) and KRM% ($P < .001$) compared with FM. At midstance, running exhibited greater ($P < .001$) KTJM than FM for each load condition; however, FM had greater KAM% ($P < .001$) and KRM% ($P = .002$) compared with running at peak vertical ground reaction force and midstance. Men exhibited greater KAM% at heel strike ($P = .02$) independent of locomotion pattern and at midstance ($P = .04$) for FM.

Conclusion: Load carriage increases KAM% to a magnitude similarly observed in populations with knee osteoarthritis, especially when executing FM. Interestingly, men exhibited greater KAM% than women, suggesting differing strategies to motor execution with relative load carriage.

Clinical Relevance: Screening recruits for greater KAM% during loaded gait tasks may identify individuals in need of specialized training to reduce the risk of knee osteoarthritis development.

Keywords: body-borne load; kinetics; load carriage; military; osteoarthritis

Osteoarthritis (OA) of the knee is a prevalent condition[26,48] primarily affecting the elderly (>65 years of age) but disproportionately affecting younger military personnel.[5,38] US warfighters experience ~3 times higher incidences of knee OA compared with civilian counterparts[5] and studies have observed a 45% incidence increase within the military within the past 10 years.[19,38] Furthermore, it is one of the leading causes of limited duty[19] and disability discharge[5] and more often affects junior enlisted members than junior officers.[5,38] Relatedly, veterans of combat-oriented roles

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(eg, infantry) have exhibited a knee OA prevalence as high as 41%.[5] These high incidences of knee OA in combat veterans and enlisted personnel implicate the physically arduous nature of combat roles in the development of knee OA. Specifically, combat roles are characterized by increased exposure to loaded gait tasks, which may explain the high incidence of knee OA in younger enlisted personnel.[5]

Because of these observed relationships of OA with physically demanding occupations,[19,34,38] it is postulated that maladaptive mechanics that increase tibiofemoral compartment loading are one etiological factor in knee OA development.[12] Peak lateral and medial compartment forces of the tibiofemoral joint occur at heel strike and ~25% of stance phase, respectively, coinciding with peak axial tibiofemoral joint reaction force (peak vertical ground reaction force [PkvGRF]).[44] Knee adduction moment (KAM) is correlated with tibiofemoral compartment load[50] and has been linked to knee OA occurrence and progression.[2,3,14,27,32,46] Further, investigations utilizing knee total joint moment (KTJM) observed that individuals with knee OA exhibited ≥45% KAM contributions to peak KTJM.[2,11,30,37,50] It has been suggested that KAM contributions to KTJM during ambulatory tasks may be indicative of future disease progression/development.[2,37] Loaded forced marching (FM) (ie, maintaining a walking pattern at a velocity one would typically jog) is a common locomotion pattern performed in the military[41,42] and has been shown to alter the mechanics observed at the knee.[10,17,20,21]

Krajewski et al[21] demonstrated that recruit-aged women exhibited ~52% KAM contributions to KTJM with additional load carriage up to 45% of body weight (BW) while executing FM. By comparison, Asay et al[2] observed a 45% KAM contribution to KTJM in a sample of patients suffering from knee OA. Krajewski et al's[21] sample consisted of all women and utilized loads that represented the lower range of typical "military-relevant" loads (ie, 20-60 kg or ~25%-80% of BW[45]), typically experienced in the early portions of recruit training. However, loads often exceed 30% of body weight in military training and operational settings.[18] Similarly, Salverda et al[35] demonstrated that recruit-aged men and women both increased peak knee frontal plane angle and adduction velocity as time progressed during loaded walking, but they did not compare sexes. Importantly, women experience greater prevalence of knee OA with more severe pain and ambulatory disruptions.[34,43] Now that combat roles are open to women, there is a need to better understand sex-specific consequences of execution/repeated exposure to load carriage tasks to inform training doctrine to help mitigate potential knee OA. Thus, 2 pertinent questions need to be addressed: (1) do greater magnitude, military-relevant loads further exacerbate KAM contribution to KTJM (Q1), and (2) are there sex-specific responses to load carriage and FM (Q2)?

Therefore, the purpose was to determine the interactive effects of military-relevant load magnitudes and locomotion patterns on KTJM, along with its planar percentage contributions in recruit-aged adults during short-duration gait tasks. The secondary purpose was a preliminary analysis to determine the effect of sex on KTJM and its planar percentage contributions. We hypothesized that (1) the greatest load magnitude would significantly increase KAM contribution to KTJM compared with lower magnitudes/no load (Q1) and that (2) FM would increase KAM compared with running due to its being an imposed locomotion pattern at that gait velocity.[21,22] Women have greater risk of knee OA compared with men in general populations,[43] suggesting sex's role in the development of knee OA. Thus, it was hypothesized that women would exhibit greater KAM contribution to KTJM compared with men regardless of experimental condition (Q2).

METHODS

Participants

Twenty healthy, recreationally active recruit-aged (18-35 years) adults participated in the study (refer to Table 1 for sample characteristics). Participants were recruited from the local area who were inexperienced with executing load carriage tasks which is similar to military recruits in the basic military training phase who are mostly unfamiliar with load carriage. The recruit phase was chosen to investigate instead of veterans as it would be preferential to identify maladaptive mechanics during this phase to facilitate potential preventative measures. Participants had to be capable of running on a treadmill for 10 minutes at 2.68 m/s (self-reported) to be included and were excluded if they had a musculoskeletal injury in the past 6 months, neuromuscular condition, or were pregnant. Written informed consent was obtained prior to participation, and the study was approved by the university institutional review board.

Procedures

Participants executed 10-minute trials (or as long as possible up to 10 minutes) of running and FM with no load

*Address correspondence to Kellen T. Krajewski, PhD, Musculoskeletal Research Center, Department of Orthopedics, Children's Hospital Colorado, University of Colorado School of Medicine, 13123 16th Avenue, Aurora, CO 80045, USA (email: kellen.krajewski@cuanschutz.edu) (Twitter: @KKrajewski25).
†Department of Sports Medicine and Nutrition, University of Pittsburgh, Pittsburgh, Pennsylvania, USA.
‡Department of Orthopedics, University of Colorado School of Medicine, Aurora, Colorado, USA.
§Biodynamics Laboratory, Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania, USA.
||Center for Lower Extremity Ambulatory Research, Rosalind Franklin University of Medicine and Science, Illinois, USA.
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Ethical approval provided by the institutional review board of University of Pittsburgh (STUDY20010093).

TABLE 1
Sample Characteristics[a]

Variable		Total (N = 20)	Men (n = 10)	Women (n = 10)	P
Age		26.15 ± 3.65	24.7 ± 3.8	27.6 ± 3.5	.09
Height, m		1.72 ± 0.08	1.80 ± 0.08	1.64 ± 0.07	<.001
Weight, kg		70.33 ± 14.33	78.62 ± 14.73	62.04 ± 13.93	.02
External load, kg	+ 45%BW	31.03 ± 4.71	34.96 ± 6.41	27.09 ± 3.01	.01
	+ 55%BW	38.13 ± 7.67	42.83 ± 8.03	33.43 ± 7.30	.01
Velocity, m/s	BW	1.74 ± 0.19	1.80 ± 0.19	1.68 ± 0.19	.17
	+ 45%BW	1.66 ± 0.19	1.61 ± 0.11	1.71 ± 0.27	.14
	+ 55%BW	1.59 ± 0.24	1.68 ± 0.27	1.49 ± 0.20	.05

[a]Data are presented as mean ± SD. Bold values indicate significance at $P \leq .05$. BW, body weight (no load); + 45%BW, additional 45% of BW; + 55%BW, additional 55% of BW.

(BW), an additional load of 45% of BW (+ 45%BW) and an additional load of 55% of BW (+ 55%BW) with 2- to 5-minute rest periods. Despite absolute loads being used in military settings, relative loads were chosen to compare sexes and control for confounds of stature. All gait tasks were performed in provided combat boots (Speed 3.0 Boot; 5.11 Tactical) to control for the influence of footwear on knee mechanics.[46] Load was distributed 40% anterior and 60% posterior to mimic military-relevant load configurations[9] and achieved with a combination of a plate carrier (Testudo Gen 2; Armored Republic) and a small weight vest (Short Plus Style Vest [≤37 kg]; MIR) or large weight vest (EZ-Vest [>37 kg]; Kensui Fitness). Weight vests were placed on top of the plate carrier and secured tightly to reduce extraneous movement of the load. Three-dimensional kinematic data were captured at 100 Hz using 12 infrared cameras (Vicon Motion Systems). Kinetic data were captured via an instrumented dual-belt treadmill (Bertec Corporation) at 1000Hz. See Figure 1 for participant setup.

First, participants executed a 10-minute familiarization trial that consisted of 5 minutes of walking at a rating of perceived exertion [RPE] effort between 8 and 10 on the 20-point Borg scale. Following the 5 minutes of walking, participants transitioned directly into jogging at an RPE-rated effort of 10 to 12. Familiarization was performed on the split-belt treadmill in provided combat boots with no load.

Following familiarization, gait transition velocity (GTV) was determined as the velocity at which the participant transitioned from walking to jogging using a ramped treadmill protocol accelerating at 0.05 m/s^2.[21] Mean GTV were established by conducting 3 trials before the performance of each load condition. Experimental trials were performed at 10% above mean GTV for that specific load condition. Data collection started once participants had reached the trial velocity and continued for 10 minutes (or as long as possible). Trials concluded early if participants verbally indicated they could no longer continue or were unable to maintain required velocity. Participants were instructed to adopt a "natural" and comfortable locomotion pattern for the run trials and to maintain a walking gait irrespective of the treadmill velocity for the FM trials. Load conditions were randomized first, and then locomotion patterns within the load condition were randomized to control for order effects. Participants were given 2 to 5 minutes rest between each trial to minimize the effects of fatigue.

Figure 1. Custom 31-marker set used to define the trunk, pelvis, and lower extremities. Circles represent retroreflective markers. Markers at the medial/lateral epicondyles (knee) and medial/lateral malleoli (ankle) were removed after the static calibration trial capture. Markers at the calcaneus and the first and fifth metatarsophalangeal joints defined the foot segment.[21]

Data Reduction

Data were processed in Visual3D (C-Motion) and analyzed in Matlab (Mathworks, Inc) with custom scripts. Biomechanical models were constructed utilizing a linked model for the trunk and lower extremities using 3-dimensional coordinates of reflective markers to calculate kinematics of the trunk, thigh, shank, and foot with the additional load applied only to the trunk segment.[21] Heel strike was identified by vGRF exceeding 50N. Midstance was defined as the instant that horizontal ground reaction force (hGRF) transitioned from negative to positive (ie, braking to propulsion). Knee moments were calculated using inverse dynamics[1] and GRFs using previously defined inertial properties of lower extremity segments.[8] Moments were normalized to system weight (body mass + mass of weight vest) to allow for comparison between participants. The mean of 30 consecutive strides was analyzed per participant at the 30% completion point of the trial.

Knee moments in all 3 planes were extracted at heel strike; midstance; PkvGRF (the instant of greatest vGRF for the support limb); peak knee flexion moment of stance phase (PkFlex); and peak knee adduction moment of stance phase peak adduction moment (PkAdd). These events were chosen due to their relation to peak tibiofemoral compartment loading events and consistency with previously reported literature.[7,11,21,44]

The KTJM was calculated utilizing the Euclidian norm of the moments of the 3 planes of motion[2]; knee flexion moment (KFM), KAM, and knee rotation moment (KRM):

$$KTJM = \sqrt{KFM^2 + KAM^2 + KRM^2}$$

Additionally, from the KTJM calculation each plane of motion moment was separated into a percentage contribution toward the TJM[2]; KFM percentage (KFM%), KAM percentage (KAM%), and KRM percentage (KRM%):

$$KFM\% = \frac{KFM^2}{TJM^2} \times 100 \quad KAM\% = \frac{KAM^2}{TJM^2} \times 100$$

$$KRM\% = \frac{KRM^2}{TJM^2} \times 100$$

Statistical Analysis

To determine the effects of sex, locomotion, and load on KTJM and its planar contributions, a Sex x Locomotion x Load (2 x 2 x 3) mixed-factor repeated-measures analysis of variance (RMANOVA) was conducted separately for each gait event (heel strike, midstance, PkAdd, PkFlex, and PkvGRF) for KTJM, KFM%, KAM%, and KRM%, respectively. If a significant 3-way interaction was observed, then simple main effects were assessed for each level of the interaction. If no significant 3-way interaction was observed, then only 2-way interactions of Load x Locomotion, Load x Sex, and Locomotion x Sex were examined. Simple main effects were performed (paired *t* tests for locomotion and RMANOVA for load) if a significant interaction was found. If no significant 2-way interaction was observed, then main effects were examined. Partial eta squared (η^2_p) was calculated as a measure of effect size with magnitudes of effect interpreted as 0.01 to 0.089 (small effect); 0.09 to 0.24 (moderate effect); and ≥0.25 (large effect)[6]. Alpha level was set at .05.

RESULTS

FM PkFlex, PkvGRF, and PkAdd occurred at 27.7 ± 18.5%, 33.6 ± 12.1%, and 43.8 ± 17.5% of stance, respectively. Similarly, running PkFlex, PkvGRF, and PkAdd occurred at 36.5 ± 19.4%, 36.2 ± 5.8%, and 38.2 ± 11.2% of stance, respectively. Henceforth, the results will be presented in order of gait event occurrence for clarity (heel strike, PkFlex, PkvGRF, PkAdd, and midstance). See Table 2 for KTJM stratified by sex. Refer to Figures 2 and 3 for the absolute and percentage planar moment contribution to KTJM, respectively.

Heel Strike

At heel strike, there was no interaction between locomotion pattern and load, but FM exhibited a greater KTJM than running (main effect locomotion [$P < .001$; η^2_p = 0.74]). Additionally, KTJM increased from BW to +55%BW (main effect of load [$P = .03$; η^2_p = 0.17]).

At heel strike, there were no interactions between locomotion pattern and load for KFM%, KAM%, or KRM%. FM had greater KFM% than running (main effect locomotion [$P < .001$; η^2_p = 0.51]). FM had less KAM% than running (main effect locomotion [$P = .01$; η^2_p = 0.29)]. KRM% for FM was less than running (main effect locomotion [$P < .001$; η^2_p = 0.66]). Moreover, BW had less ($P = .02$) KRM% than +45%BW (main effect of load [$P = .04$; η^2_p = 0.17]).

When examining the effect of sex (Q2) at heel strike, there were no significant findings for KTJM. However, at heel strike women had greater KFM% than men (main effect sex [$P = .02$; η^2_p = 0.26]). Moreover, women had less KAM% than men (main effect sex [$P = .02$; η^2_p = 0.26]). For KRM%, there were no effects of sex.

At PkFlex

At PkFlex, there were no significant effects of load, locomotion, or sex on KTJM or KRM%. However, there was a significant interaction between load and locomotion ($P = .04$; η^2_p = 0.19) for KFM%, with post hoc analysis failing to reveal further significant differences. While not significant, during running, KFM% was lower for +45%BW and +55%BW than BW. Likewise, +45%BW and +55%BW were lower for running compared with FM (Figure 3, D-F).

Last, there was a significant interaction between load and locomotion ($P = .03$; η^2_p = 0.20) for KAM% at PkFlex, with post hoc analysis failing to reveal further significant

TABLE 2
Knee Total Joint Moment (Nm/kg)[a]

Gait Event	Locomotion	Load	Total	Men (n = 10)	Women (n = 10)
Heel strike[b]	Run	BW	0.31 ± 0.14	0.26 ± 0.04	0.36 ± 0.18
		+45%BW	0.23 ± 0.06	0.24 ± 0.04	0.23 ± 0.08
		+55%BW	0.25 ± 0.08	0.25 ± 0.06	0.26 ± 0.10
	Forced march	BW	0.56 ± 0.22	0.52 ± 0.19	0.60 ± 0.26
		+45%BW	0.53 ± 0.17	0.47 ± 0.17	0.60 ± 0.15
		+55%BW	0.48 ± 0.18	0.50 ± 0.20	0.47 ± 0.17
Peak flexion moment	Run	BW	0.95 ± 0.37	0.95 ± 0.36	0.96 ± 0.40
		+45%BW	0.75 ± 0.34	0.81 ± 0.46	0.69 ± 0.17
		+55%BW	0.82 ± 0.39	0.95 ± 0.37	0.68 ± 0.38
	Forced march	BW	0.95 ± 0.37	0.95 ± 0.36	0.96 ± 0.40
		+45%BW	0.97 ± 0.35	0.89 ± 0.35	1.05 ± 0.36
		+55%BW	0.97 ± 0.44	1.00 ± 0.53	0.94 ± 0.34
Peak vGRF[c]	Run[d]	BW	1.64 ± 0.49	1.71 ± 0.55	1.56 ± 0.43
		+45%BW	1.14 ± 0.33[f]	1.20 ± 0.31	1.08 ± 0.35
		+55%BW	1.17 ± 0.49[f]	1.11 ± 0.52	1.22 ± 0.48
	Forced march	BW	0.73 ± 0.33	0.77 ± 0.35	0.69 ± 0.33
		+45%BW	0.87 ± 0.31	0.88 ± 0.39	0.87 ± 0.23
		+55%BW	0.95 ± 0.39	1.02 ± 0.41	0.89 ± 0.38
Peak adduction moment[c]	Run	BW	0.69 ± 0.57	0.44 ± 0.21	0.97 ± 0.71
		+45%BW	0.58 ± 0.36	0.50 ± 0.17	0.66 ± 0.47
		+55%BW	0.40 ± 0.14	0.38 ± 0.15	0.44 ± 0.14
	Forced march	BW	0.64 ± 0.51	0.44 ± 0.21	0.86 ± 0.66
		+45%BW	0.54 ± 0.21	0.53 ± 0.27	0.56 ± 0.13
		+55%BW	0.76 ± 0.46	0.95 ± 0.58	0.57 ± 0.13
Midstance[e]	Run	BW	1.23 ± 0.90	0.98 ± 0.36	1.47 ± 1.20
		+45%BW	0.62 ± 0.27[f]	0.62 ± 0.22	0.62 ± 0.32
		+55%BW	0.62 ± 0.33[f]	0.61 ± 0.36	0.63 ± 0.32
	Forced march	BW	0.27 ± 0.12	0.28 ± 0.11	0.27 ± 0.14
		+45%BW	0.34 ± 0.09[f]	0.32 ± 0.10	0.36 ± 0.08
		+55%BW	0.31 ± 0.14[f]	0.34 ± 0.14	0.28 ± 0.14

[a]Data are presented as mean ± SD. BW, body weight (no load); +45%BW, additional 45% of BW; +55%BW, additional 55% of BW.
[b]Main effect of locomotion (for total sample); forced march greater than run.
[c]Interaction between load and locomotion.
[d]Simple effect of locomotion (for total sample); run greater than forced march.
[e]Main effect of locomotion (for total sample); run greater than forced march.
[f]Significantly ($P \leq .05$) different from BW load condition within the same locomotion pattern.

differences. However, during running, KAM% was greater for +45%BW and +55%BW compared with BW. Likewise, the loaded conditions for running had greater KAM% than FM (Figure 3, D-F).

At PkvGRF

At PkvGRF, there was an interaction between load and locomotion ($P < .001$; $\eta^2_p = 0.49$) for KTJM. Running exhibited greater KTJM than FM for each load condition (simple main effect of locomotion): BW ($P < .001$); +45%BW ($P = .002$); +55%BW ($P = .01$). During running, BW had a greater KTJM than the +45%BW ($P = .02$) and +55%BW ($P = .01$) load conditions.

FM had lower KFM% than running (main effect of locomotion [$P < .001$; $\eta^2_p = 0.56$]). Conversely, FM had greater KAM% (main effect of locomotion [$P < .001$; $\eta^2_p = 0.54$]) and KRM% (main effect of locomotion [$P < .001$; $\eta^2_p = 0.52$]) than running.

At PkAdd

At PkAdd, there was an interaction between load and locomotion ($P = .03$; $\eta^2_p = 0.24$) for KTJM, with post hoc analysis failing to reveal further significant differences. However, FM KTJM was greater than running for +55%BW, whereas KTJM was relatively the same between locomotion patterns for BW and +45%BW (Table 2). There were no effects of sex on KTJM at PkAdd.

For KFM% at PkAdd, there was a significant interaction between locomotion and sex ($P = .04$; $\eta^2_p = 0.26$). During running, men had greater ($P = .05$) KFM% than women. While not significant, women exhibited greater KFM% during FM compared with running, whereas men exhibited greater KFM% during running compared with FM (Figure 3, J-L).

For KAM% at PkAdd, there was a significant interaction between load and locomotion ($P = .01$; $\eta^2_p = 0.26$), with post hoc analysis failing to reveal further significant differences. However, for the +55%BW load condition,

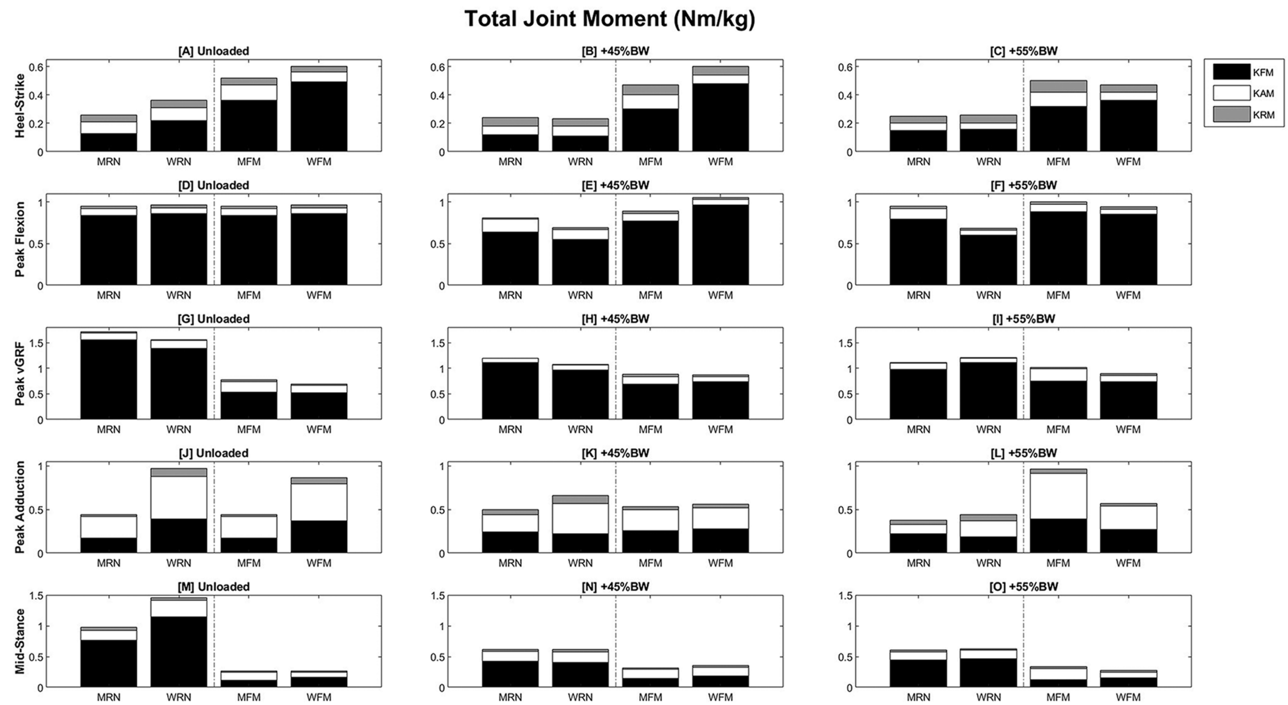

Figure 2. Knee total joint moment (KTJM) normalized to system weight (body weight [BW] + load carriage weight). Panels A-C represent heel strike, D-F represent peak flexion moment, G-I represent peak vertical ground reaction force, J-L represent peak adduction moment, and M-O represent midstance. (A-O) Regardless of condition, there were no significant differences in KTJM between men and women. (A-C) At heel strike, forced marching had a greater KTJM than running, largely driven by the larger knee flexion moment (KFM). (M-O) Conversely, at midstance, running exhibited larger KTJM than forced marching. While KFM was a larger contributor to the greater KTJM for running, knee adduction moment (KAM) and knee rotation moment (KRM) also increased with load magnitude. (L) At peak adduction during the +55%BW load condition, forced marching KTJM was greater than running. Moreover, KAM was a greater contributor to this KTJM. +45%BW, additional load of 45% of body weight; +55%BW, additional load of 55% of body weight; MFM, men's forced marching; MRN, men's running; vGRF, vertical ground reaction force; WFM, women's forced marching; WRN, women's running.

FM KAM% was greater than running, while KAM% was relatively similar between locomotion patterns for BW and +45%BW load conditions (Figure 3, J-L). Additionally, there was an interaction between locomotion and sex ($P = .02$; $\eta^2_p = 0.30$) for KAM% at PkAdd. Post hoc analysis failed to reveal any significant differences, but women had greater KAM% for running than FM , whereas men had greater KAM% for FM than running (likely contributing to the significant interaction) (Figure 3, J-L).

For KRM% at PkAdd, there was a significant interaction between load and locomotion ($P < .001$; $\eta^2_p = 0.42$). During the +55%BW load condition, running had greater KRM% ($P < .001$) than FM. Additionally, during running, +55%BW KRM% was greater ($P < .001$) than BW.

Midstance

At midstance, there was an interaction between load and locomotion for KTJM ($P = .001$; $\eta^2_p = 0.33$). Running exhibited greater KTJM than FM for each load condition: BW ($P < .001$); +45%BW ($P < .001$); and +55%BW ($P < .001$). Additionally, there was a simple main effect of load on running ($P = .001$; $\eta^2_p = 0.30$) with BW being greater than +45%BW ($P = .02$) and +55%BW ($P = .04$). Likewise, there was a simple main effect of load for FM as well ($P = .05$; $\eta^2_p = 0.15$) with post hoc pairwise comparisons failing to reveal differences.

At midstance, there was no interaction between locomotion pattern and load for KFM%, KAM%, or KRM%. FM had less KFM% than running (main effect locomotion [$P < .001$; $\eta^2_p = 0.60$]). Furthermore, FM had more KAM% (main effect locomotion [$P < .001$; $\eta^2_p = 0.53$]) and KRM% than running (main effect locomotion [$P = .002$; $\eta^2_p = 0.42$]).

At midstance, there were no effects of sex for KTJM, KFM%, or KRM%. However, for KAM% there was an interaction between sex and locomotion ($P = .05$; $\eta^2_p = 0.20$). Women had less KAM% than men for FM only at BW ($P = .04$) and +55%BW ($P = .01$) load conditions.

DISCUSSION

The aim of this study was to determine the interactive effects of military-relevant load magnitudes, locomotion

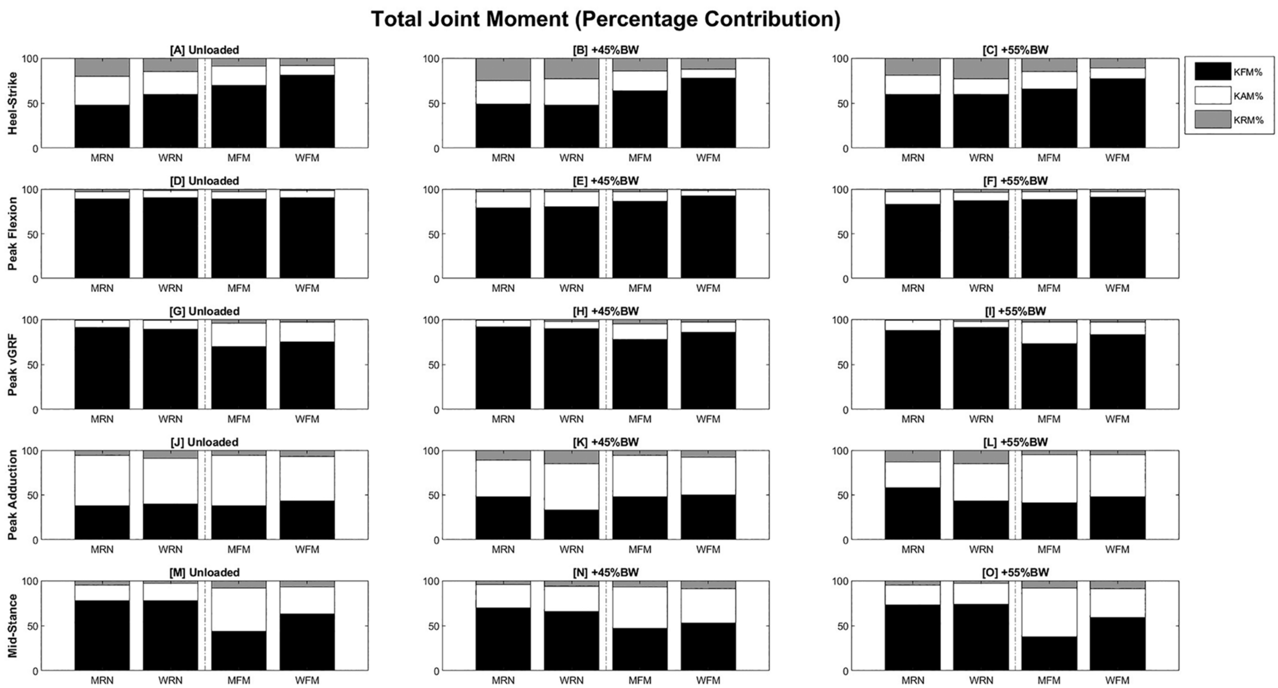

Figure 3. Planar percentage contributions to knee total joint moment. Panels A-C represent heel strike, D-F represent peak flexion moment, G-I represent peak vertical ground reaction force, J-L represent peak adduction moment, and M-O represent midstance. At heel-strike (A-C), running (RN) had a greater knee adduction moment percentage (KAM%) and knee rotation moment percentage (KRM%). However, at peak vertical ground reaction force (vGRF) (G-I) and midstance (M-O), forced marching (FM) exhibited the significantly greater KAM%. Interestingly, the KAM% of FM at peak adduction (J-L) and midstance (M-O) had comparable values to those observed in knee osteoarthritis–affected populations. + 45%BW, additional load of 45% of body weight; + 55%BW, additional load of 55% of body weight; KFM%, knee flexion moment percentage; MFM, men's forced marching; MRN, men's running; WFM, women's forced marching; WRN, women's running.

patterns, and sex on potential kinetic mechanisms that might explain the high incidence of knee OA observed in military personnel. KTJM and its planar contributions were chosen due to its established, positive association with knee OA.[2] Moreover, knee moment magnitude is positively correlated with velocity but does not change the overall shape of the knee moment waveform or the planar contribution,[15,24] making KFM%, KAM%, and KRM% ideal outcome measures for comparing conditions at different velocities. The most interesting finding of this study was that women had less KAM% compared with men when performing with military-relevant, relative load magnitudes, both while running and during FM, contrary to our hypothesis. Additionally, our results reinforce previous research indicating that running and FM with load carriage increase frontal plane KAM%.[21,28,35] Likewise, larger KTJM and planar contributions for running and FM were dependent on gait event, in support of our previous work.[21] Although relative KTJM decreased as load increased for most gait events, these changes were likely attributable to the decrease in velocity from BW to + 55%BW (see Table 1). It should also be reiterated that KTJM was normalized to system weight (BW + weight vest), thus in absolute terms, KTJM increased substantially with increases in load carriage magnitude. Hereon, the discussion will focus on effects between locomotion patterns and sex at the same load condition to remove potential confounds of velocity to interpretation of relative values.

While running exhibited more favorable sagittal plane joint kinematics at heel strike compared with FM in a previous cohort,[10] in the present investigation, KAM% and KRM% were greater at each load magnitude during running. This may be a consequence of difficulty controlling/managing the attenuation of the external load at initial impact. The load carriage system initially generated a force transmitted superior-to-inferior and increased the transverse moment of the trunk that must be counteracted. The lack of reliable sensory information due to the external nature of the load and its associated forces made it difficult to properly calibrate foot placement for optimal heel strike. But once the foot was planted on the ground, the participant was capable of regaining control of the load exhibited by the shift to greater KFM% as the stride progressed (Figure 3). Indeed, adapting motor behavior to regulate the kinetics of load has previously been demonstrated through the freezing of the trunk degrees of freedom to ameliorate transverse momentum of an external load.[25] During running, greater vertical displacement of the center of mass will occur; while some participants may have attempted to control this aspect of their gait, previous work would indicate that the task goal of maintaining trial velocity supersedes other cost functions.[22,23] Consequently, the external load "bounces" on the participant's trunk more during running.[33] Increased independent motion of the load carriage system during the running gait task has the potential to introduce asynchronous forces that are difficult to control through lower extremity kinematic modulation stride to stride (further evidenced by the greater PkvGRF KTJM during running compared with FM at the same velocity [Figure 2, G-I]). The sample population in the present study were novices with respect to load carriage and may have had insufficient time/task exposure to develop the appropriate physiological capacity and appropriate motor behavior(s), which could explain the increase in KAM% and KRM% during running at heel strike despite its being a more natural locomotion pattern, compared with FM. This latter point is an important consideration for recruit populations, as >30% load carriage magnitudes are introduced during training.

Conversely, at PkvGRF and midstance, running had ~2 times greater KTJM than FM at each load condition (refer to Table 2), but KFM% contribution was greater to KTJM than for FM (~73% versus ~50% [Figure 3, G-I and M-O]). This increase of KTJM for running is likely due to a combination of the greater vertical displacement of the center of mass and the knee extensors being properly aligned to attenuate force and assist in propulsion, supporting previous observations regarding running and sagittal plane joint stiffness.[4,16] As gait velocity increases, the transition from walking to running increases the stiffness (Δmoment $\div$ Δangle) of the knee joint.[16] The addition of external load(s) (20-35 kg) yields a ~19% increase in knee joint stiffness when performing the task at the same velocity.[4] By contrast, FM results in a more stiff-legged gait (less stance phase knee excursion in the sagittal plane),[10] and thus the knee joint is not properly aligned to attenuate or generate force for propulsion. Krajewski et al[20] has demonstrated that during loaded FM, mechanical work shifts proximally to the hip in recruit-aged healthy women. To generate propulsion, the hip extensor musculature is likely preferentially recruited to compensate for the more extended limb at midstance and the impaired ability of the plantarflexors to contribute to propulsion at the velocity exceeding gait transition velocity.[31] Consequently, an abnormal alignment of the lower extremity joints may occur to optimize hip extensor contributions to the required propulsion as the limb transitions from load acceptance to propulsion. This could explain the observed KAM% of 14% to 53% for FM at PkvGRF, PkAdd, and midstance, indicating greater medial tibiofemoral compartment loading during ~33% to 50% of stance. Moreover, the observed KAM% of ~50% (see Figure 3, M-O) at midstance is comparable to KAM% observed in knee OA confirmed populations.[2] While it is recognized that this observation is not direct evidence of causality, it does indicate the necessity for prospective investigations to ascertain the extent that FM with load may contribute to the development of knee OA in military populations, considering its prevalence and the consequences for both the individual warfighter's health and the readiness of the US military.[5]

Since women exhibit a greater prevalence of knee OA,[34,43] it was hypothesized that they would demonstrate greater KAM% compared with men when executing loaded gait tasks. Surprisingly, our preliminary analysis of sex found that men exhibited greater KAM% than women at heel strike, and at PkAdd for both locomotion patterns, and midstance for FM only. Despite the relatively small group sizes (n = 10) these significant differences of sex had moderate to large effect sizes (η^2_p) of 0.20 to 0.30.[6] It is plausible that the differences observed in men and women are attributed to the differences in trial velocities between men and women (see Table 1). However, Landry et al[24] found that increasing velocity from preferred walking speed to 150% of preferred speed simply increased magnitude of moments in all planes and did not alter the planar contribution for healthy controls or knee OA–affected patients. Indeed, in healthy young adults, only walking speeds of 0.30 to 0.70 m/s significantly changed the shape of the knee moment waveform during stance by flattening the curve and almost entirely eliminating the contribution of net external moments of the knee[15] In the present sample, the slowest mean trial velocity was 1.49 m/s, which is well above the aforementioned range of velocities that would significantly affect knee moments in terms of shape. Furthermore, men and women only differed ~0.14 m/s across load conditions (see Table 1). Thus, it is less likely the observed differences in planar contributions between sexes are attributed solely to differences in velocity.

To date, few studies have directly examined the effect of sex on lower extremity biomechanics during loaded gait tasks. When examining sagittal plane knee moments (flexion/extension) during loaded walking at ~1.30 m/s, there were no differences between sexes when utilizing relative loads up to 30% of BW[40] or standard absolute military loads.[28] Loverro et al[28] demonstrated that comparisons of absolute load magnitudes while walking at 1.35 m/s increased peak knee abduction and adduction moments regardless of sex, but women did decrease sagittal plane knee excursion with increasing load compared with men. Similarly, while running at 4.0 m/s with 35 kg, Brown et al[4] observed women having 15% greater sagittal knee stiffness compared with men, which was dictated by decreased knee flexion excursion and greater knee flexion moments. Our work further supports these findings, as there were differences in the percentage contributions of KTJM, with women exhibiting greater KFM%. Previously observed decreased knee excursion[28] and increased knee flexion stiffness[4,39] may potentially serve as the sex-mediated mechanism for FM and running, respectively, to potentially mitigate increasing load magnitudes. Furthermore, our use of relative loads could explain why we observed a sex-specific difference in planar contributions at the knee.[28,40]

Limitations

There are a few limitations for the present investigation that are important to acknowledge to caution interpretation of results. The military uses absolute load magnitudes regardless of stature[28] and walks/forced marches/overground runs on varying terrain, whereas this investigation used relative loads and examined gait on an instrumented treadmill. While this omission limits ecological validity to military settings, relative loads and an instrumented treadmill were chosen to confirm sex-specific differences, control for confounds of anthropometrics, and accurately capture joint kinetics. Our findings support previous research using absolute loads confirming sex-specific responses.[28] Nonetheless, our results, particularly the moderate to large effect sizes of observed sex differences, further suggest that dimorphic responses to load carriage for various gait tasks may not be due solely to sex but rather the relative load intensity,[40] as women are smaller than men on average.[28] Given the relatively small sample size for sex comparisons, more research is needed to support this conclusion, and effect sizes observed here can be used for future sample size calculations. Additionally, the experimental sample was novice to load carriage unlike active-duty personnel. Therefore, the results can only be generalized to recruit populations, but future research should include veterans and active-duty warfighters to determine whether differences in mechanics contribute to knee OA at this stage of their career. Last, it must be reiterated that this investigation is cross-sectional and does not provide direct evidence of knee OA mechanisms. However, since our results are similar in magnitude to knee OA–affected populations,[2] we believe it reasonably supports this postulation and warrants further prospective research to determine how knee mechanics adapt with load carriage experience to elucidate potential biomechanical mechanisms of knee OA. Moreover, future research should use imaging techniques that track skeletal motion with better accuracy, such as biplane radiography, to examine tibiofemoral kinematics of the articulating surfaces to determine changes in areas of contact in response to changes in gait and load.

CONCLUSION

Load carriage is an inevitable component of ground close combat operations, and the requirement to carry heavy loads over extended periods remains. Identification of recruits at greater risk of musculoskeletal injury such as knee OA is paramount to warfighters' health and readiness.[5] Examining the planar contribution of moments to KTJM at lower relative load magnitudes during early stages of recruit training could inform training strategies for at-risk recruits. Indeed, tibiofemoral joint-crossing muscle forces influence knee contact forces,[13,29,36,49] and muscle coordination training utilizing biofeedback principles has preliminary evidence supporting its effectiveness for retraining muscle activation patterns to reduce knee contact forces during walking in young adults of recruit age.[47]

Regardless of locomotion pattern, relative load carriage increases KAM% and KRM% in healthy physically active recruit-aged adults as indicated in the present investigation and supported by other research using absolute loads.[28,35] However, divergent planar contributions to KTJM between men and women suggest relative load magnitude might be a greater contributor to aberrant knee mechanics than the sex phenotype. The latter point should be considered most during the recruit training phase, as recruits are unfamiliar with executing gait tasks with load carriage and thus more susceptible to injury while under high magnitude load. Most troublesome is the observation of large KAM% during FM with loads of +45%BW and +55%BW that are comparable to individuals with rapidly progressing knee OA.[2] Specifically, men exhibited greater KAM% and KRM% compared with women regardless of relative load condition, which may explain the high incidence of knee musculoskeletal injuries, such as knee OA, observed in men in the military.[5,19,38]

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