Lower-limb joint kinetics in jump rope skills performed by competitive athletes.

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Abstract

The purpose of this study was to characterise lower-limb joint kinetics during consecutive double unders and speed step sprints performed by competitive jump rope athletes, and to compare these measurements to running. Sixteen adolescent competitive jump rope athletes performed consecutive double under, speed step, and running trials while motion capture and ground reaction force data were collected. Lower limb joint moments, power, and work were calculated using an inverse dynamics approach and discrete measurements were compared between skills. Peak ground reaction forces were similar between movements; however, knee and hip joint kinetics were distributed differently between double unders and speed step. In general, double unders were characterised by an increased reliance on knee joint kinetics, while speed step was characterised by an increased reliance on hip joint kinetics. Peak ankle moments were 9-20% greater in speed step when compared to double unders and running ($p \leq 0.050$), and peak negative ankle power was 39-114% greater in double unders and speed step when compared to running ($p \leq 0.002$). These findings may have important implications for injury risk and load management in jump rope athletes or other individuals that incorporate jump rope into their training programs.

Keywords: biomechanics; musculoskeletal system; lower extremity; rope skipping; hopping

Introduction: Jump rope is an activity widely used in physical education, fitness, and sport training programs for its cardiorespiratory (Quirk & Sinning, 1982), strength (Duzgun et al., 2010), agility (Miyaguchi et al., 2015), coordination (Ozer et al., 2011), and bone health (Pettersson et al., 2000) benefits. One million students across 4,000 schools in Canada participate in Jump Rope for Heart programs annually (Heart and Stroke Foundation of Canada, n.d.). In addition to its use in fitness and recreation, jump rope is a growing competitive sport with clubs in 51 countries (International Jump Rope

Union, n.d.). Athletes compete individually and as teams in events including timed speed, consecutive triple unders, and freestyle (International Jump Rope Union, n.d.). While there is a wide variety of skills performed by these athletes, jump rope may be characterised by highly repetitive hopping with closely coupled upper limb movements controlling rope turning.

It has been hypothesised that the development of overuse injuries, though multifactorial and variable between specific injuries, is associated with repetitive loading and insufficient recovery time (Edwards, 2018). Repetitive loading, especially at high magnitudes, results in microdamage accumulation in both tendon and bone (Pattin et al., 1996; Wren et al., 2003). Without adequate repair, the accumulation of damage may eventually lead to injury (e.g., tendinopathy or stress fracture) (Edwards, 2018). Tendinopathies, medial tibial stress syndrome, and stress fractures have all been reported in competitive jump rope (Ollivierre, 1994); these injuries are also prevalent in other jumping/running sports such as volleyball and basketball (Eerkes, 2012; Gordon et al., 2014).

Previous jump rope studies have reported ground reaction force (GRF) (Jang et al., 2017; Kim et al., 2017; Pittenger et al., 2002; Shek et al., 2005), plantar pressure (Shek et al., 2005), and joint angle (Jang et al., 2017; Kim et al., 2017) parameters. Most of the studies quantified external loading parameters or kinematics for one- or two-legged single unders (one revolution of the rope per jump) or double unders (two revolutions per jump; see Online Supplementary video 1). Both movements involve continuous hopping, where the lower limbs are relatively rigid and the majority of jumping forces are produced by the ankle and knee (Lamontagne & Kennedy, 2013). Shek et al. (2005) also quantified GRF and plantar pressure for speed step (see Online Supplementary video 2) and consecutive triple unders (three revolutions per jump; see Online Supplementary video

3), performed by one elite jump rope athlete. Consecutive triple unders require greater jump height and rope speed compared to double unders and are competed among athletes age 15 years and older. Speed step, also referred to as ‘alternating step,’ is primarily used for timed speed events. Unlike single and multiple unders, speed step involves jumping from one leg to the other using a stepping motion that enables the athlete to achieve a rapid pace. Shorter ground contact time has also been observed during speed step compared to single or multiple unders (Shek et al., 2005).

To date, jump rope biomechanics studies have focused on GRF and kinematics. Only two of these studies have investigated multiple unders or speed step (Kim et al., 2017; Shek et al., 2005), which are fundamental, repetitive skills that make up a large proportion of a competitive athlete’s training. No study has reported joint kinetics, which are indicative of the magnitude and distribution of musculoskeletal loading. Thus, the purpose of this study was to characterise joint kinetics during consecutive double unders and speed step sprints performed by competitive jump rope athletes. Parameters were also compared to running, which is a widely studied repetitive loading activity with a high incidence of lower-limb overuse injuries (Fukuchi et al., 2017; Messier et al., 2018; Schache et al., 2011; Scott & Winter, 1990; Tenforde et al., 2011). Differences exist between double unders and speed step with respect to kinematics, jump height, and ground contact time (Shek et al., 2005), which are likely to influence joint kinetic parameters. For example, a previous study observed differences in the distribution of joint moments throughout the lower limb associated with different ground contact times during hopping (Hobara et al., 2010). Therefore, we hypothesised that the distribution and magnitude of lower limb joint kinetic parameters would be different between double unders and speed step.

Methods: Sixteen adolescent competitive jump rope athletes (14 F and 2 M, 14.3 ± 1.8 years, 1.63 ± 0.08 m, 59.7 ± 8.1 kg) were recruited from teams in Alberta, Canada. Athletes competed at the provincial level or above in the previous season and had no musculoskeletal injuries in the three months prior to testing that would keep them from training. All testing procedures were approved by the university's Conjoint Health Research Ethics Board. All participants, and guardians for participants aged 15 or younger, provided written informed consent.

Each athlete performed their typical warm-up, which generally consisted of a series of dynamic stretches and light bodyweight exercises targeting the lower and upper limbs, and core. Retroreflective markers were then placed at landmarks on the pelvis, dominant leg, and shoe (i.e., sacrum, right and left anterior superior iliac spine and greater trochanters, proximal anterior thigh, distal anterior thigh, lateral thigh, lateral and medial knee, proximal anterior shank, distal anterior shank, posterior shank, lateral and medial malleoli, dorsal foot, first metatarsal head, third metatarsal head, fifth metatarsal head, distal hallux, and calcaneus) (Bruce et al., 2019). Following a static motion-capture trial, participants performed running, consecutive double unders, and speed step sprint trials while motion capture (240 Hz, 8 high-speed Eagle cameras; Motion Analysis Corporation, Santa Rosa, CA, USA) and force platform (1 force plate, 2400 Hz, Kistler Instrument Corp., Amherst, NY, USA) data were collected synchronously using Cortex software (v5.0, Motion Analysis Corporation, Santa Rosa, CA, USA). Participant anthropometrics (height, mass, lower limb segment lengths and circumferences) were recorded at the end of the session.

Running trials were performed at $3.5 \text{ m/s} \pm 5\%$ along a 15 m lane. This speed was chosen because it is commonly used in running studies, enabling comparison to previous literature (Fukuchi et al., 2017; Schache et al., 2011). Participants completed practice runs

prior to data collection until they were able to achieve the target speed consistently. Three successful trials were collected. Trials were repeated if the dominant leg did not land on the force platform, the participant did not achieve the target speed, or if the participant appeared to change their cadence in order to target the force platform.

For the jump rope movements, athletes used their own custom wire ropes (R1 Speed, JumpNrope, Ltd., CO, USA, or Elite Surge, BuyJumpRopes.net, WA, USA, with coated or uncoated stainless steel cords) for testing. Athletes performed single and double unders to practice prior to the trial. Each athlete then performed 20-30 consecutive double unders (Online Supplementary video 1) at self-selected jump frequency with their dominant foot on the force platform and non-dominant foot on the ground adjacent. If the athlete drifted such that the marked foot landed partially off the force platform or the non-marked foot landed on the force platform, verbal instructions were provided until that athlete was correctly aligned. Frontal plane video of the feet and force platform was recorded for the purpose of identifying incorrectly aligned landings to be excluded from data analysis.

Athletes then performed the speed step trial. A practice trial was completed at approximately 70% of maximum speed. Following a minimum one minute rest, each athlete performed a maximal 10 s sprint using the speed step (Online Supplementary video 2). The trial was repeated if more than one miss (where the rope stopped due to catching on the body) occurred.

Three of the participants (2F, 1M, 15-17 years, 1.57-1.67 m, 56.9-61.2 kg) were also able to complete a trial of 15-25 consecutive triple unders (Online Supplementary video 3). An opportunistic analysis was performed using the same protocol as double unders.

Data were analysed using MATLAB software (v.r2016b, Mathworks, Inc., USA). GRF data were down-sampled to match motion capture data. Data were then cut to isolate the ground contact phases. For running trials, heel strike was defined as the first data point ≥ 20 N. Toe-off was defined as the first data point following heel strike ≤ 20 N. For the consecutive double unders and triple unders, the ground contact phase following the first double/triple under was excluded, as the first jump is usually higher to accommodate the initial slower rope velocity. Contact phases where the marked foot was partially off the force platform, or where the non-marked foot was on the force platform (identified through a conservative visual inspection of the video recorded during the trial) were excluded. The first 10 contact phases of the remaining double unders, and the first 8 contact phases of the remaining triple unders, were selected for analysis. Touch-down and toe-off were defined using a 20 N threshold similar to the running trials. For the speed step trial, the first two contact phases of the marked leg were excluded, as the athlete increases speed over the initial steps. The next 10 contact phases corresponding to the marked leg were selected for analysis. Again, touch-down and toe-off were defined using a 20 N threshold.

Retro-reflective markers were used to define local reference frames for the pelvis, thigh, shank, and foot. Cardan segment and joint angles were calculated using a flexion-extension, abduction-adduction, internal-external rotation sequence. Segment masses, centre of mass locations, and moments of inertia for the thigh, shank, and foot were obtained using anthropometric measures and equations described by Vaughan et al. (1999). An inverse dynamics approach was used to calculate joint moments in the global reference frame and these were subsequently transformed into the local reference frame of the distal segment. Joint power was calculated by multiplying the joint moment by the joint angular velocity. Segment angular accelerations for inverse dynamics analysis and

joint angular velocities for joint power calculations were obtained using the finite difference method. A 4th order zero-lag Butterworth filter was used to smooth the raw GRF, joint moment, and power data at the 95th percentile frequency of the distal vertical reaction force (Edwards, Troy, & Derrick, 2011). Vertical instantaneous loading rate (VILR) was calculated as the slope of the vertical GRF using the finite difference method. Impulse was calculated as the time-integral of the vertical GRF. Positive and negative joint work were calculated as the time-integral of positive and negative joint power, respectively.

Cycle-averaged peak vertical GRF, impulse, peak vertical instantaneous loading rate (VILR), peak net joint moments, peak positive and negative joint powers, and positive and negative joint work were quantified for each athlete. Analysis of joint kinetics was limited to those occurring about the segment medial-lateral (i.e., flexion-extension) axis, the predominant axis of motion for double unders, speed step, and running. Each variable was checked for normality using the Shapiro-Wilk test and visual examination of histograms and Q-Q plots. Repeated measures ANOVAs were used to test for differences among the movements. Where relevant, post-hoc paired t-tests with a Bonferroni correction were used to determine differences between pairs of running, double unders, and speed step. If data were non-normal, a log transform was applied and normality was checked again. If the data were still not normally distributed, a Friedman test was used to test for differences between movements. Wilcoxon signed-rank tests were used for post-hoc analysis where relevant. Effect sizes (partial η^2 for ANOVAs and average Spearman rho for Friedman tests) were calculated for main effects. All statistical tests were performed in SPSS (v.24.1.1, IBM, Armonk, NY, USA) with a criterion alpha-level of 0.05.

Results: The average cadence for double unders and speed step was 2.0 ± 0.2 and 4.9 ± 0.4 jumps/s, respectively. Significant main effects were observed for stance time, impulse, and VILR ($p \leq 0.003$, $\eta^2 \geq 0.379$, Table 1). Stance time was 27% and 41% shorter (95% CI: 0.051 - 0.085 s and 0.080 - 0.120 s), and vertical impulse was 30% and 43% lower (CI: 51.2 – 81.7 and 70.8 – 112.7 BW·s), for double unders and speed step, respectively, when compared to running ($p \leq 0.001$). Peak VILR was 47% greater during speed step when compared to double unders ($p < 0.001$, CI (ratio of means): 1.26 – 1.72). No differences in peak vertical GRF were observed ($p = 0.240$).

Significant main effects were observed for all joint kinetic parameters ($p \leq 0.023$, $\eta^2 \geq 0.223$) except peak positive ankle power, peak negative knee power, and negative ankle work (Table 1). Peak ankle moment and negative power were greater during speed step than running and double unders ($p \leq 0.050$, CI_{moment} : 0.02 - 29.9 Nm and 15.3 - 46.0 Nm, CI_{power} (ratio): 1.45 – 3.16 and 1.17 – 2.03). Negative ankle power was also greater during double unders when compared to running ($p = 0.002$, CI (ratio): 1.14 – 1.70). Positive ankle work was lower during speed step than double unders and running ($p \leq 0.001$, CI: 4.5 – 14.3 J and 7.3 – 17.5 J). Peak knee moment (Figure 1) and positive work (Figure 2) were lower in speed step than running and double unders ($p \leq 0.004$, CI_{moment} : 27.9 – 77.1 Nm and 50.5 – 105.0 Nm). Negative knee work was also lower in speed step than running ($p = 0.008$) and peak knee moment was greater in double unders when compared to running ($p = 0.036$, CI_{moment} : 1.4 – 49.1 Nm). All hip joint kinetic parameters were lower in double unders when compared to running and speed step ($p \leq 0.023$, Table 1, Figures 1 and 2). Hip positive work was lower, and peak powers were greater, in speed step when compared to running ($p \leq 0.034$, CI_{work} : 6.9 - 20.3 J, $CI_{\text{power, positive}}$ (ratio): 1.21 – 2.28, $CI_{\text{power, negative}}$ (ratio): 1.07 – 3.06).

While stance time was similar to double unders, all other measures (peak vertical GRF, impulse, VILR, peak joint moments, peak joint powers, and joint work) tended to be larger in triple unders when compared to double unders (Table 2, Figure 3).

Discussion and implications: The purpose of this study was to characterise joint kinetics during consecutive double unders and speed step in competitive jump rope athletes, and to compare these measurements to running. Although peak GRF was similar between movements, knee and hip joint kinetics were distributed differently between double unders and speed step. In general, double unders were characterised by an increased reliance on knee joint kinetics, while speed step was characterised by an increased reliance on hip joint kinetics. Peak ankle moments were 9-20% greater in speed step when compared to double unders and running ($p \leq 0.050$), and peak negative ankle power was 39-114% greater in double unders and speed step when compared to running ($p \leq 0.002$). These findings may have important implications for injury risk and load management in jump rope athletes or other individuals that incorporate jump rope into their training programs.

Across all movements, the greatest joint kinetic parameters were observed at the ankle. Peak ankle moments were 20% and 9% greater in speed step than double unders and running, respectively, and peak negative ankle power was 39-114% greater in the jump rope skills when compared to running. These larger loads about the ankle joint, produced primarily by the triceps surae muscles, are transmitted to the calcaneus via the Achilles tendon (Fukashiro et al., 1995; Lamontagne & Kennedy, 2013). Greater forces through the Achilles tendon would also result in greater ankle joint contact force and bending moments applied to the tibia (Scott & Winter, 1990). For musculoskeletal tissues, such as tendon and bone, it is well known that fatigue life measurements are heavily influenced by loading magnitude (Pattin et al., 1996; Wren et al., 2003), but it is also

important that the number of loading cycles is considered (Edwards, 2018). Speed step and double unders are usually performed in a series of short bouts (10 s to 5 min). In a typical training session, an athlete may perform a cumulative total of 20 minutes of speed step at an average of 90% of their maximum speed, resulting in 2,646 steps per foot. Adding cycles from consecutive double unders, typically ~500 per session, would result in a total of 3,146 cycles per foot. For comparison, a 30-minute run with a cadence of 85 strides/minute (Fukuchi et al., 2017) would result in 2,550 strides. It is well known that runners have a high incidence of overuse injuries, such as Achilles tendinopathy and tibial stress fractures (Tenforde et al., 2011). Given the similar or greater magnitudes of musculoskeletal loading and the high number of cycles associated with jump rope speed/double unders training sessions, a high incidence of overuse injuries at the ankle and lower limb would be expected in jump rope athletes. Indeed, these types of injuries have been documented (Ollivierre, 1994).

Although peak GRF was not different between movements, differences in joint kinetic patterns were observed at the knee and hip. Peak knee extension moment was minimal in speed step, being 61% lower when compared to running. The lower knee moment could be explained, in part, by the shorter ground contact time as a previous study of vertical hopping observed a decrease in peak knee moment with increasing hop frequency (and associated decrease in ground contact time) (Hobara et al., 2010). Leg stiffness was also previously observed to increase with hop frequency, and this was achieved primarily through changes at the knee and hip (Hobara et al., 2010). The stepping motion used in speed step explains the distinct patterns in knee and hip joint power (Figure 2). Unlike double unders and running, knee and hip extension occurs in the first half of ground contact, followed by flexion in the second half (Figure 4). The positive power at the knee and hip in the first half of ground contact indicates concentric

muscle contraction extending the joints. The negative power at the knee, corresponding with a flexion moment, in the first half of ground contact during speed step indicates eccentric muscle activity slowing down extension of the knee. The active extension of the leg in the first half of ground contact, combined with the shorter contact time, may explain the greater VILR compared to double unders, and the larger peak negative power at the ankle compared to double unders and running. In the second half of ground contact, negative power and moment, and positive angular velocity were observed at the hip. Taken together, this indicates eccentric muscle activity acting to resist hip flexion. Both knee and hip flexion were observed throughout the second half of ground contact during speed step, in contrast with extension at both joints during double unders and running (Figure 4). This suggest the majority of propulsive force during speed step is generated at the ankle.

In double unders, the kinetic parameters were highest at the ankle and knee, and this distribution of joint loading is consistent with submaximal vertical hopping (Souza et al., 2010). Compared to running, peak knee extension moment and positive power were 29% and 69% greater, respectively, and all hip joint kinetic parameters were 36-84% lower. Similarly, peak knee moment and positive work were 233% and 179% greater in double unders when compared to speed step. Joint kinetic parameters are indicative of the magnitude of musculoskeletal loads. It may be important to consider the different distribution of joint kinetics at the ankle, knee, and hip between double unders and speed step when creating training programs for jump rope athletes or when choosing which jump rope skill to incorporate into cross training programs. For example, an athlete specialising in multiple unders and freestyle events may consider incorporating additional exercises to improve knee extension strength into their off-season training. Athletes in sports other than jump rope often use double unders in cross training workouts to increase

cardiovascular demand. Speed step could be used as an alternative in a workout that involves other exercises which impose a heavy load on the knee.

Competitive jump rope athletes aged 15 and older compete in consecutive triple unders, instead of double unders. Kinetic parameters across all joints tended to be greater during triple unders when compared to double unders (Table 2, Figure 3). Similar to double unders, athletes typically perform fewer triple unders (100-500) per session compared to speed step or running training. Due to the ages of participants in the current study, only three athletes were able to complete 15-25 consecutive triple unders. Given the greater magnitudes of the joint kinetic parameters, further work evaluating the training load associated with triple unders performed by older athletes is warranted.

A limitation of the present study is the large range of ages, statures, and skill levels (speed scores and competitive experience) present in the participant group tested. It is possible that technique differences may exist between athletes of different ages or skill levels (Jang et al., 2017; Kim et al., 2017). While the sprint speeds observed in this study (4.9 Hz) are representative of typical scores for this age group at the provincial level in Alberta, greater speeds (7.5 Hz) have been observed at the international level (International Jump Rope Union, n.d.). Further work is needed to determine how speed influences joint kinetics during speed step. The broad inclusion criteria were necessary due to the limited number of jump rope athletes near the university. While the competitive jump rope population is small relative to sports such as running, these results are relevant to other populations. For example, Cross-Fit athletes perform double unders in training and competition, often in combination with running and other exercises.

Conclusion: Joint kinetics in competitive athletes performing jump rope skills were on the order of magnitude, and in some instances higher, than joint kinetics in running. The high joint kinetic magnitudes, especially at the ankle, combined with high repetition

may suggest these athletes and others incorporating jump rope into training may be at risk of developing overuse injuries. Differences in joint kinetic distributions at the knee and hip between jump rope skills should also be considered when structuring training programs.

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Table 1. Mean (95% CI) ground reaction force and joint kinetic parameters at the ankle, knee, and hip for running, consecutive double unders, and speed step.

Measure	Running	Double Unders	Speed Step	p-value	Effect size
Contact time (s)	0.245 (0.232-0.258)	0.178 (0.165-0.190) a	0.145 (0.134-0.156) a,b	<0.001	0.892
vGRF max (BW)	2.54 (2.45-2.63)	2.62 (2.44-2.79)	2.66 (2.51-2.82)	0.240	-
Impulse (BW·s)	214.9 (192.2-237.7)	148.5 (132.7-164.2) a	123.1 (110.7-135.6) a,b	<0.001	0.882
VILR max (BW/s)*	63.2 (54.2-73.6)	48.9 (43.1-55.5)	71.8 (62.2-83.0)b	0.003	0.379
Peak joint moment (Nm)					
ankle	169.2 (149.9-188.4)	153.5 (136.3-170.7)	184.1 (163.8-204.5) a,b	<0.001	0.480
plantarflexion					
knee extension	85.9 (68.9-103.0)	111.2 (88.4-134.0) a	33.4 (19.2-47.7) a,b	<0.001	0.704
hip extension	140.5 (123.5-157.4)	68.5 (57.0-80.0) a	121.0 (106.0-136.0) b	<0.001	0.704
Peak positive joint power (W)					
ankle**	614.9 (212.9)	746.1 (230.9)	650.1 (220.0)	0.099	-
knee*	192.3 (155.2-238.2)	324.3 (236.0-445.7) a	216.8 (141.3-178.6)	0.023	0.223
hip*	396.3 (329.6-476.4)	116.9 (80.0-170.0) a	657.7 (526.0-824.1) a,b	<0.001	0.828
Peak negative joint power (W)					
ankle*	544.5 (448.7-662.2)	756.8 (650.1-881.0) a	1166.8 (922.6-1472.3)a,b	<0.001	0.559
knee*	385.5 (267.9-554.6)	262.4 (185.4-371.5)	332.7 (232.8-476.4)	0.251	-
hip*	191.4 (140.9-260.0)	122.2 (95.5-156.3) a	345.9 (271.6-441.6) a,b	<0.001	0.574
Positive work (J)					
ankle	40.2 (34.8-45.6)	37.2 (32.3-42.2)	27.8 (24.2-31.4) a,b	<0.001	0.646
knee**	12.4 (8.8)	15.6 (13.3)	5.6 (5.6) a,b	0.002	0.362
hip	35.7 (28.9-42.5)	5.7 (3.8-7.5) a	22.1 (19.0-25.2) a,b	<0.001	0.840
Negative work (J)					
ankle	41.0 (39.1-50.1)	38.5 (32.7-44.3)	33.1 (28.4-37.8)	0.167	-
knee**	13.7 (17.6)	11.2 (15.0)	7.4 (4.2) a	0.018	0.200
hip**	5.5 (5.0)	2.7 (3.5) a	10.0 (5.3) b	0.002	0.488

BW = body weight. vGRF = vertical ground reaction force. VILR = vertical instantaneous loading rate.

Effect sizes are reported as partial η^2 , except when Friedman tests were performed (**), where the calculated effect size is reported as average Spearman rho.

* geometric means and confidence intervals, back-transformed from $\log_{10}$ -transformed data

** values reported are median (IQR)

a: different compared to RUN ($p < 0.05$)

b: difference between DU and SS ($p < 0.05$)

Table 2. Cycle-averaged mean ground reaction force parameters and joint work at the ankle, knee, and hip during consecutive double unders (DU) and consecutive triple unders (TU) for each participant who successfully completed the TU trial.

	Athlete 1		Athlete 2		Athlete 3	
	TU	DU	TU	DU	TU	DU
Contact time (s)	0.152	0.152	0.200	0.217	0.188	0.187
vGRF max (BW)	3.69	2.97	3.50	2.85	2.61	2.54
Impulse (BW·s)	178.2	137.2	203.8	188.5	199.6	142.3
VILR max (BW/s)	93.0	57.0	62.1	45.0	57.9	43.3
Positive work (J)						
ankle	47.2	36.3	67.8	56.8	62.1	45.2
knee	24.8	4.0	40.3	32.5	24.6	3.6
hip	6.9	12.6	7.0	3.6	7.6	0.6
Negative work (J)						
ankle	-60.5	-44.4	-73.5	-63.2	-65.8	-41.2
knee	-23.5	-4.0	-40.9	-30.6	-28.2	-6.1
hip	-1.1	-2.0	-7.9	-4.6	-11.5	-2.2

BW = body weight. vGRF = vertical ground reaction force. VILR = vertical instantaneous loading rate.

Figure 1. Ensemble average curves for vertical ground reaction force and sagittal plane lower limb joint moments during running, double unders, and speed sprint. Shaded areas represent standard deviation.

BW = body weight. Ankle: positive is dorsiflexion, negative is plantarflexion. Knee: positive is extension, negative is flexion. Hip: positive is flexion, negative is extension.

Figure 2. Ensemble average curves for sagittal plane lower limb joint power during running, double unders, and speed sprint. Shaded areas represent standard deviation.

Figure 3. Joint moments and power during double unders (DU) and triple unders (TU) for each of the three athletes who completed both trials.

Ankle moment: positive is dorsiflexion, negative is plantarflexion. Knee moment: positive is extension, negative is flexion. Hip moment: positive is flexion, negative is extension.

Figure 4: Ensemble average curves for ankle, knee, and hip angular velocity during the ground contact phase of running, double unders, and speed step sprints.

Ankle: positive is dorsiflexion, negative is plantarflexion. Knee: positive is extension, negative is flexion. Hip: positive is flexion, negative is extension.