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ORIGINAL RESEARCH

Differences in Muscle Demand and Joint Contact Forces Between Running and Skipping

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Skipping has been proposed as a viable cross-training exercise to running due to its lower knee contact forces and higher whole-body energy expenditure. However, how individual muscle forces, energy expenditure, and joint loading are affected by differences in running and skipping mechanics remains unclear. The purpose of this study was to compare individual muscle forces, energy expenditure, and lower extremity joint contact forces between running and skipping using musculoskeletal modeling and simulations of young adults ($n = 5$) performing running and skipping at 2.5 $m{\cdot}s^{-1}$ on an instrumented treadmill. In agreement with previous work, running had greater knee and patella contact forces than skipping which was accompanied by greater knee extensor energetic demand. Conversely, skipping had greater ankle contact forces and required greater energetic demand from the uniarticular ankle plantarflexors. There were no differences in hip contact forces between gaits. These findings further support skipping as a viable alternative to running if the primary goal is to reduce joint loading at the commonly injured patellofemoral joint. However, for those with ankle injuries, skipping may not be a viable alternative due to the increased ankle loads. These findings may help clinicians prescribe activities most appropriate for a patient's individual training or rehabilitation goals.

***Keywords*:** metabolics, musculoskeletal model, simulation, gait

Skipping is a unique gait because it uses alternating, 2 consecutive but different right steps (a step and a hop) followed by 2 left steps. Skipping is also unique in that it features both the single-limb stance and flight phases observed in running as well as a short double-limb stance phase as in walking.[1] During skipping, 1 leg executes a step and a hop followed by a step and a hop by the contralateral limb. Although not an often observed gait in adults, skipping has been used as a transitional rehabilitation activity between walking and running[2] and is a common warm-up exercise for athletes across a variety of sports.[3–5] In addition, skipping was recently suggested to be a viable supplemental cross-training activity to running.[6] The lower vertical ground reaction forces (GRFs),[2,6] lower knee joint contact forces[7], and higher metabolic cost[7,8] experienced during skipping may represent a lower joint load, yet still aerobically demanding, form of exercise.

Recent work comparing skipping and running found the increased metabolic cost of skipping was associated with a greater vertical displacement of the body while the lower maximum vertical GRF and knee contact forces were associated with the shorter step lengths that occur in skipping.[7] However, while the majority of running-related injuries affect the knee,[9] injuries to the hip[10] and ankle[11] are also common in runners, but it is unknown whether skipping also reduces joint forces at these other joints. Muscles are the primary contributors to energy expenditure and the generation of GRFs and joint contact forces. Thus, the differences in kinematics, kinetics, and energetics between running and skipping suggest that there are differences in muscle demand between these gaits which have yet to be determined. Understanding the differences in joint loading between skipping and running would provide insight into the mechanical stimuli underlying injury potential of each gait mode and inform clinical decision-making for exercise prescription.

For example, although skipping has lower knee joint contact forces per gait cycle, skipping has a greater number of load cycles due to the 2 unique steps per gait cycle. It is unclear whether participation in skipping reduces the cumulative mechanical load experienced over a given distance compared with running. This is a clinically relevant kinetic variable due to the dose-dependent nature of the articular cartilage response to physical activity observed in animal models of osteoarthritis.[12,13] Additionally, greater daily cumulative knee joint loads have been observed to discriminate between people with and without knee osteoarthritis[14] and predict greater medial tibiofemoral joint cartilage damage over a 2-year period in older adults.[15] Finally, among people with a history of ACL reconstruction[16] or knee osteoarthritis,[17] knee joint cartilage recovers at a slower rate following running than in healthy runners, prompting recommendations for less frequent running in these populations.[18] Alternative modes of exercise with a lower dose of mechanical joint loading may be beneficial in such clinical populations to avoid accumulation of catabolic articular cartilage effects observed in animal exercise models. Previous work has observed that while the skipping hop has greater knee contact forces than the skipping step, the running step has greater knee contact forces than both the skipping hop and step and a running cycle has greater compressive patellofemoral contact forces per kilometer than a skipping cycle.[7] However, it is unclear how joint loads compare between skipping and running steps and cycles at the hip and ankle.

Musculoskeletal modeling and simulation techniques enable investigations of the underlying neuromuscular mechanisms that contribute to experimental biomechanical and metabolic observations. Simulation studies determined that the hip extensors (gluteus maximus), knee extensors (rectus femoris and vasti), and ankle

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plantarflexors (gastrocnemius and soleus) are primary contributors to the biomechanical subtasks of running.[19–21] Lower peak knee extensor moments, but greater peak hip extensor and ankle plantarflexor moments, have been observed in skipping compared with running,[6] which further suggest potential differences in muscle forces and energy expenditure between gaits. In addition, a subsequent study[7] identified lower knee joint contact forces during skipping than in running using a primarily 2-dimensional model of the knee with lumped muscle models of the quadriceps, hamstrings, and gastrocnemius muscle groups and lateral support forces.[22,23] To build on these initial insights of joint contact forces during skipping and running, leveraging a musculoskeletal model of the entire lower extremity would permit an investigation of the joint contact forces at the hip and ankle in addition to the knee. Such an analysis would also help identify which muscles contribute to the greater metabolic cost of skipping and suggest which muscles may be differentially affected by a skipping training or rehabilitation regimen.

Therefore, the purpose of this study was to compare individual muscle metabolic cost and forces as well as lower extremity joint contact forces between skipping and running. As part of a training or rehabilitation regimen, aerobic exercise may be prescribed for a given time (eg, a 30-min run) or for a given distance (eg, a 5-km run). Thus, measures of metabolic cost and muscle and joint forces as a function of time (metabolic power and impulse, respectively) and of distance (cost of locomotion and force and impulse per kilometer, respectively) were assessed to provide insight into whether skipping and running differentially impact muscle demand and joint loading per unit distance and per unit time.

Methods

Participants and Experimental Data Collection

Five healthy young adults (2 females; 22.4 [2.2] y; 1.70 [0.06] m; 74.5 [12.7] kg) provided written informed consent to participate. The study protocol was approved by the East Carolina University Institutional Review Board. The 3-dimensional (3D) positions of 58 reflective markers placed on joint centers, bony landmarks, and tracking clusters on the shank and thigh were sampled at 200 Hz from a 10-camera motion capture system [Qualisys Medical AB] during a static calibration trial (see Table S1 in the Supplementary Material [available online] for complete marker set). Of these 58 markers, 42 were retained while participants completed 3 10-second running and skipping trials. The participants performed the running and skipping trials at a set speed of 2.5 $m{\cdot}s^{-1}$ on an instrumented dual-belt treadmill (Bertec USA) from which GRFs were collected at 1000 Hz. Participants were provided the opportunity to practice each gait condition at the test speed. After practice, the running and skipping trials were performed in a randomized order with 1-minute rest between trials. Bilateral electromyography (EMG) data sampled at 1000 Hz were simultaneously collected from the gluteus maximus, gluteus medius, rectus femoris, vastus medialis, long head of the biceps femoris, medial gastrocnemius, soleus and tibialis anterior.

Musculoskeletal Models and Simulations

For each participant, the most representative running and skipping cycles were identified using a functional median distance depth method.[24] A running (run) cycle was defined as right heel strike to subsequent right heel strike, and a skipping (skip) cycle was defined as right heel strike of the initial right step (skip 1) to the subsequent initial right step heel strike (Figure 1). A run cycle includes single stance phases for right and left limbs, whereas a skip cycle includes 2 right limb (skip 1 and skip 2) and 2 left limb stance phases.[6,7] In OpenSim (version 3.3; SimTK),[25] a full-body 12 segment model with 29 degrees of freedom, including 5 degrees of freedom for each arm controlled by coordinate actuators, and 92 musculotendon actuators[19] were scaled for each participant by minimizing the difference in the locations of the experimental markers collected during the static calibration trial and the model's virtual markers. Next, for each representative running and skipping cycle, a least squares problem was solved to determine the model's body segment kinematics that reproduced the experimental marker data by minimizing the distance between the experimental and virtual markers on the model.[26] To improve the dynamic consistency between the model kinematics and experimental GRFs, a residual reduction algorithm fine-tuned the model mass properties and joint kinematics.[26] Muscle forces were estimated by computed muscle control (CMC)[27,28] with constraints such that the muscle excitation timing and patterns were consistent with those of the experimentally measured EMG data.[29] For each participant, the EMG of each muscle from the respective run or skip cycle were normalized by the muscle's maximum value observed during the 10-second trial. Then, for each time point during the cycle, the excitation range was constrained using participant- and muscle-specific windows about the normalized EMG value such that each muscle's experimentally observed activation pattern was reproduced by the simulation. The maximum muscle excitation could not exceed 1, and the minimum excitation could not fall below 0.02. Furthermore, to ensure that CMC was muscle-driven, the peak isometric forces of all muscles in the model were uniformly strengthened until the peak reserve torque actuator magnitudes were less than 10% of the peak joint moment for all coordinates.

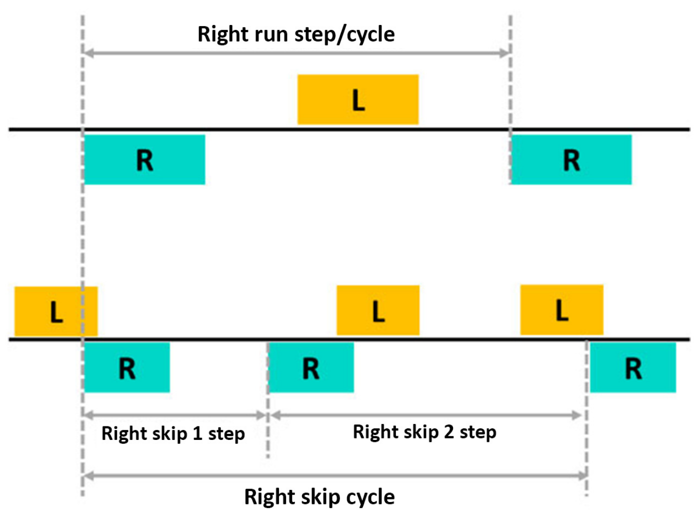

Figure 1 — Definitions of running and skipping steps and cycles on the right limb. For skipping, a step was defined as the period from one right heel strike to the subsequent right heel strike (including the stance phase and subsequent flight phase). The skip cycle was defined as the sum of the skip 1 and skip 2 steps. For running, the run cycle was the same as the run step, which was defined as the period from one right heel strike to the subsequent right heel strike.

Analyses

Muscle forces from CMC were integrated over run, skip 1, and skip 2 periods to determine the individual muscle impulses, which were then normalized to distance traveled to compare impulses between run and skip cycles (cumulative load per kilometer). The Umberger 2010 Muscle Metabolics probe[30,31] in OpenSim determined the instantaneous muscle metabolic power, which was integrated over each cycle and normalized by body mass to quantify muscle energy expenditure as a measure of the energy expended by each muscle during a single run or skip cycle. Muscle metabolic power for the entire run or skip cycle was calculated by dividing the muscle energy expenditure by the cycle duration to account for differences in the duration of an individual cycle between gaits. The cost of locomotion of the run and skip cycles was calculated for each muscle by dividing the muscle's energy expenditure by the cycle length (in kilometers) during each cycle to account for differences in the distance traveled during an individual cycle between gaits. Muscle force impulses and metabolic measures were then summed within functional groups (Table 1). For each gait, whole-body energy expenditure was calculated as the sum of the muscle energy expenditure from all muscles in the model. Whole-body metabolic power and cost of locomotion were then calculated from the whole-body energy expenditure.

The 3D acetabulofemoral (hip), tibiofemoral (knee), patellofemoral (patella) and talocrural (ankle) joint contact forces were calculated using the joint reaction analysis in OpenSim, which computes the internal joint loading as the force transferred between model segments due to all loads acting on the system including the muscle forces.[32] The 3D and resultant joint contact force impulses were calculated at each joint by time integrating the forces during the stance phases of the run, skip 1, and skip 2 periods. In addition, joint contact force impulses were normalized by the distance travelled over the run or skip cycle.

Statistics

The Lilliefors test was used to assess the normality of the data. Separate 1-way repeated-measures analyses of variance compared muscle force impulses, stance phase joint contact force peaks and impulses, and spatiotemporal gait parameters between run, skip 1, and skip 2 steps. The step velocity and cadence data were not normally distributed, so the Friedman test was used to test for differences between steps in these parameters. Bonferroni post hoc tests identified pairwise differences between steps. Paired *t* tests compared whole-body and individual muscle contributions to energy expenditure, metabolic power, and the cost of locomotion, muscle force impulses per distance traveled, joint contact force peaks and impulses per distance traveled and spatiotemporal parameters between run and skip cycles. The stride duration data were not normally distributed, so the paired-samples Wilcoxon signed-rank test assessed for differences in cycle duration between gaits. All statistical analyses were performed in MATLAB 2020b with an α value of .05 set a priori.

Results

Whole-body energy expenditure was significantly greater ($P = .009$) during skipping (32.75 [4.04] J·kg^{-1}) than running (20.45 [4.54] J·kg^{-1}). There were no significant differences between gaits in whole-body metabolic power ($P = .271$) or cost of locomotion ($P = .382$), though on average, skipping had greater whole-body metabolic power (31.73 [4.78] W·kg^{-1}) and cost of locomotion (11.92 [1.74] $\times 10^3$ J·kg^{-1}·km^{-1}) than running (28.81 [6.75] W·kg^{-1} and 11.14 [2.73] $\times 10^3$ J·kg^{-1}·km^{-1}, respectively).

During skipping, the energy expenditure was 0.46 (0.18) J·kg^{-1} greater in TRUNK ($P = .005$), 0.77 (0.38) J·kg^{-1} greater in GLUTE ($P = .011$), 1.27 (0.59) J·kg^{-1} greater in HAMS ($P = .009$), 0.51 (0.33) J·kg^{-1} greater in RF ($P = .025$), 0.47 (0.30) J·kg^{-1} greater in GAS ($P = .023$), 0.73 (0.20) J·kg^{-1} greater in SOL ($P = .001$) and 0.72 (0.27) J·kg^{-1} greater in TA ($P = .004$) than in running (Figure 2A). There were no differences in energy expenditure for the 3 remaining muscle groups ($P > .05$). VAS had 0.72 (0.41) W·kg^{-1} greater metabolic power ($P = .018$; Figure 2B) and 224 (110) J·kg^{-1}·km^{-1} greater cost of locomotion ($P = .010$; Figure 2C) during running than skipping, while SOL had 0.29 (0.22) W·kg^{-1} greater metabolic power ($P = .041$) and 103 (69.3) J·kg^{-1}·km^{-1} greater cost of locomotion ($P = .029$) during skipping than running. There were no differences in metabolic power or cost of locomotion for all other muscle groups ($P > .05$).

All muscle groups had greater muscle force impulses in the run step than in skip 1 ($P \leq .031$) and/or skip 2 ($P \leq .048$), with differences between steps ranging from 2.3 (1.7) N.s·kg^{-1} in GAS (run > skip 2) to 11.1 (3.2) N.s·kg^{-1} in TRUNK (run > skip 1) (Figure 3A). When compared with skip 1, skip 2 muscle force impulses were 8.3 (2.1) N.s·kg^{-1} greater in TRUNK ($P < .001$), 2.5 (1.8) N.s·kg^{-1} greater in BFSH ($P = .018$), 2.3 (0.5) N.s·kg^{-1} greater in RF ($P = .001$), 4.1 (1.4) N.s·kg^{-1} greater in GAS ($P = .001$), and 5.5 (4.3) N.s·kg^{-1} greater in SOL ($P = .038$). When compared between cycles, impulses were 1832 (1401) N.s·kg^{-1}·km^{-1} greater in TRUNK ($P = .043$), 1124 (844.5) N.s·kg^{-1}·km^{-1}

Table 1 Muscles Included in Each Group Based on Biomechanical Function

Analysis group	Muscle(s)
TRUNK	Erector spinae, external oblique, internal oblique
GLUTE	Gluteus maximus, gluteus medius, gluteus minimus, piriformis, gemelli
IP	Iliacus, psoas
HAMS	Biceps femoris long head, semimembranosus, semitendinosus, gracilis
RF	Rectus femoris
VAS	Vastus lateralis, vastus intermedius, vastus medialis
GAS	Medial gastrocnemius, lateral gastrocnemius
BFSH	Biceps femoris short head
SOL	Soleus, tibialis posterior, flexor digitorum, flexor hallucis, peroneus brevis, peroneus longus
TA	Tibialis anterior, extensor digitorum, extensor hallucis, peroneus tertius

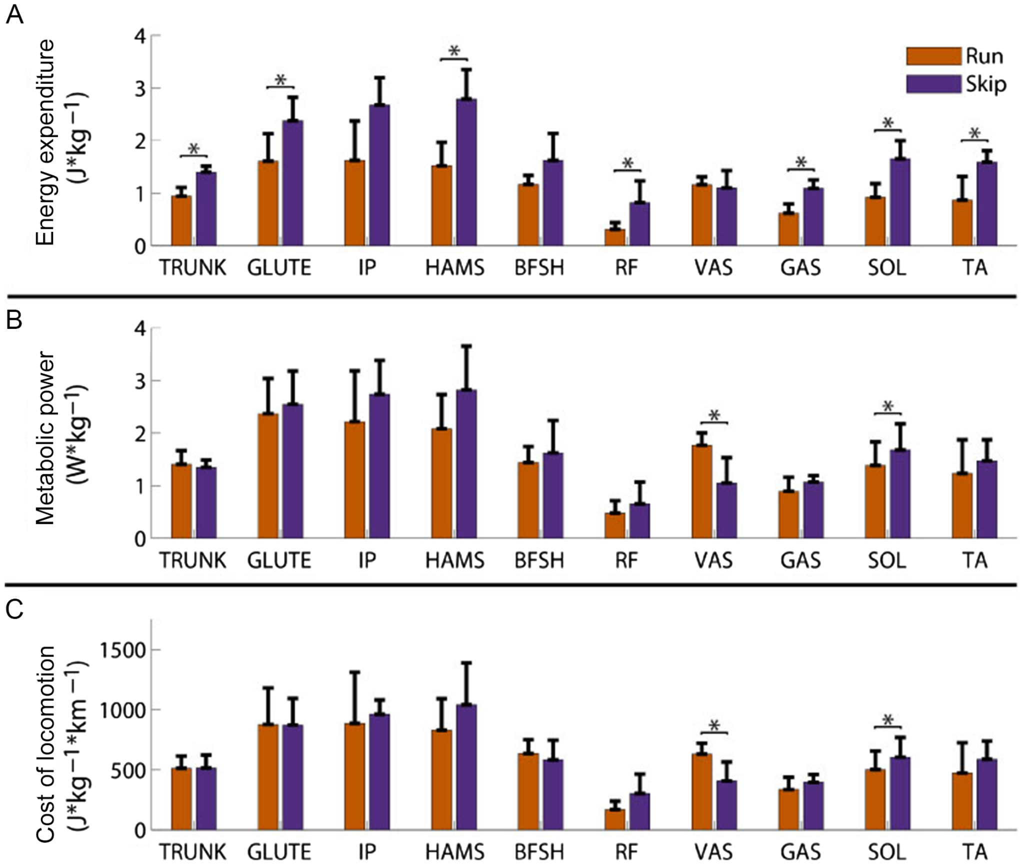

Figure 2 — Muscle energetics during running and skipping. Energy expenditure (A), metabolic power (B), and cost of locomotion (C) during running and skipping cycles for individual muscle groups. * Statistically significant difference between cycles ($P < .05$).

greater in GAS ($P = .041$), and 2262 (1713) $N.s{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in SOL ($P = .042$) in the run compared with the skip cycle (Figure 3B).

The joint that experienced the largest contact forces differed between steps. The greatest contact forces during the run step were at the knee, the greatest contact forces during the skip 1 step were at the hip, and the greatest contact forces during the skip 2 step were at the ankle (Figure 4). The compressive joint contact force magnitudes were much greater than the shear forces and will be the focus of the results described. The shear force results are reported in the Supplementary Material (available online). The run and skip 1 steps had 53.3 (9.8) $N{\cdot}kg^{-1}$ and 33.8 (21.1) $N{\cdot}kg^{-1}$ greater peak compressive patella forces ($P \leq .004$), respectively, than skip 2 (Figure 5A). The skip 2 step had a 24.6 (25.7) $N{\cdot}kg^{-1}$ greater peak ankle compressive force than the skip 1 step ($P = .048$). Per distance traveled (Figure 5B), the peak compressive patella force was 1.8 (0.4) $\times 10^4$ $N{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in the run cycle than the skip cycle ($P = .013$), but the peak compressive ankle force was 3.3 (1.3) $\times 10^4$ $N{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in skip than the run cycle ($P = .006$).

Joint contact impulses differed between steps at every joint except the hip joint (Figure 5C). At the knee, the run step had a 5.7 (4.5) $N.s{\cdot}kg^{-1}$ greater compressive impulse than skip 2 ($P = .034$). At the patella, the run and skip 1 steps had a 5.2 (1.4) $N.s{\cdot}kg^{-1}$ and 3.1 (2.4) $N.s{\cdot}kg^{-1}$ greater compressive impulse, respectively, than the skip 2 step ($P \leq .021$). Per distance traveled, the run cycle had a 931 (537) $N.s{\cdot}kg^{-1}{\cdot}km^{-1}$ greater compressive patella impulse ($P = .018$), whereas the skip cycle had a 2474 (1784) $N.s{\cdot}kg^{-1}{\cdot}km^{-1}$ greater compressive ankle ($P = .036$) impulse (Figure 5D).

The peak resultant patella force was 53.6 (9.6) $N{\cdot}kg^{-1}$ greater in run ($P < .001$) and 34.0 (21.3) $N{\cdot}kg^{-1}$ greater in skip 1 ($P = .004$) than in skip 2 (Figure 6A). In addition, the peak resultant ankle force was 25.6 (26.4) $N{\cdot}kg^{-1}$ greater in skip 2 than skip 1 ($P = .044$). Per distance traveled, the peak resultant patella force was 1.8 (0.4) $\times 10^4$ $N{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in the run cycle ($P < .001$), but the peak resultant ankle force was 3.3 (1.3) $\times 10^4$ $N{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in the skip cycle ($P = .006$) (Figure 6B). There were no differences in peak hip and knee contact forces between steps ($P \geq .264$) or cycles ($P \geq .149$). The knee contact impulse was 5.6 (4.5) $N.s{\cdot}kg^{-1}$ greater during run than skip 2 ($P = .040$), and the patella contact impulse was 5.2 (1.4) $N.s{\cdot}kg^{-1}$ greater during run ($P = .001$) and 3.1 (2.4) $N.s{\cdot}kg^{-1}$ greater during skip 1 ($P = .021$) than skip 2 (Figure 6C). Per distance traveled, the patella joint impulse was 935.8 (538.4) $N.s{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in the run cycle ($P = .018$); however, the ankle joint impulse was 2423 (1754) $N.s{\cdot}kg^{-1}{\cdot}km^{-1}$ greater in the skip cycle ($P = .037$) (Figure 6D).

Discussion

To gain further insight into the differences in whole-body energy expenditure and knee joint contact forces between skipping and running, this study leveraged a full-body musculoskeletal model to investigate differences in energy demand at the muscle level and 3-dimensional lower extremity joint contact forces between these

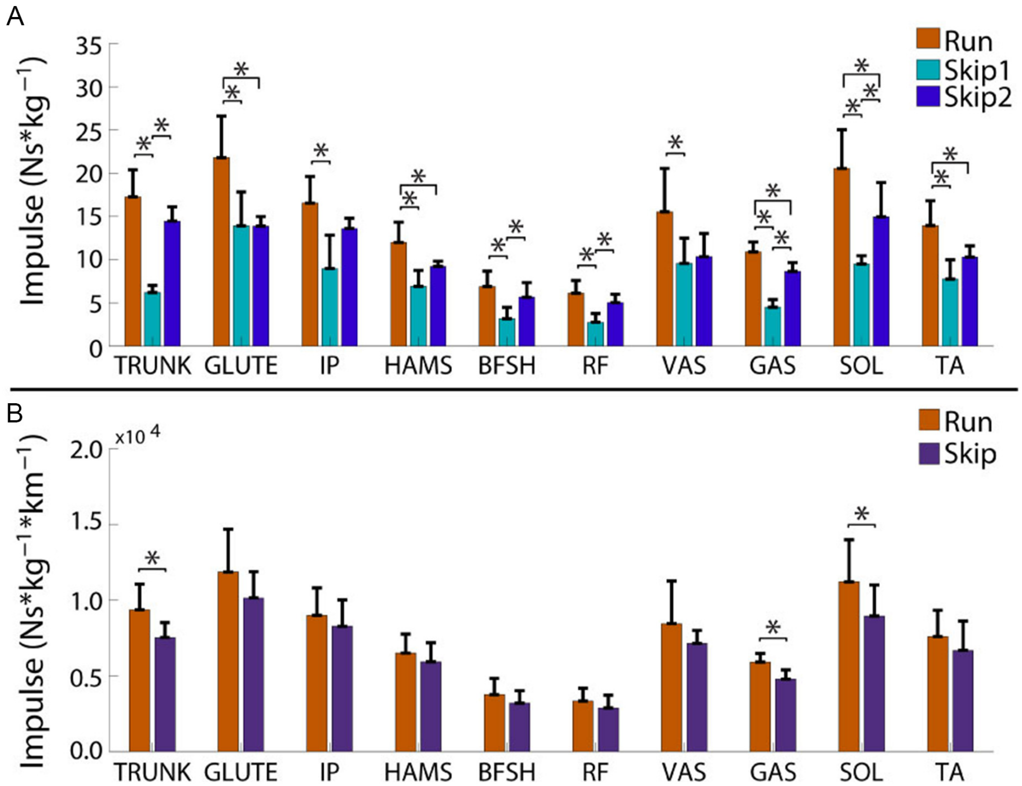

Figure 3 — Muscle force impulses during running and skipping. Muscle force impulses during running and skipping (A) steps and (B) cycles. Muscle force impulses over the run and skip cycles were normalized to cycle length. * indicates statistically significant difference between cycles or strides ($P < .05$).

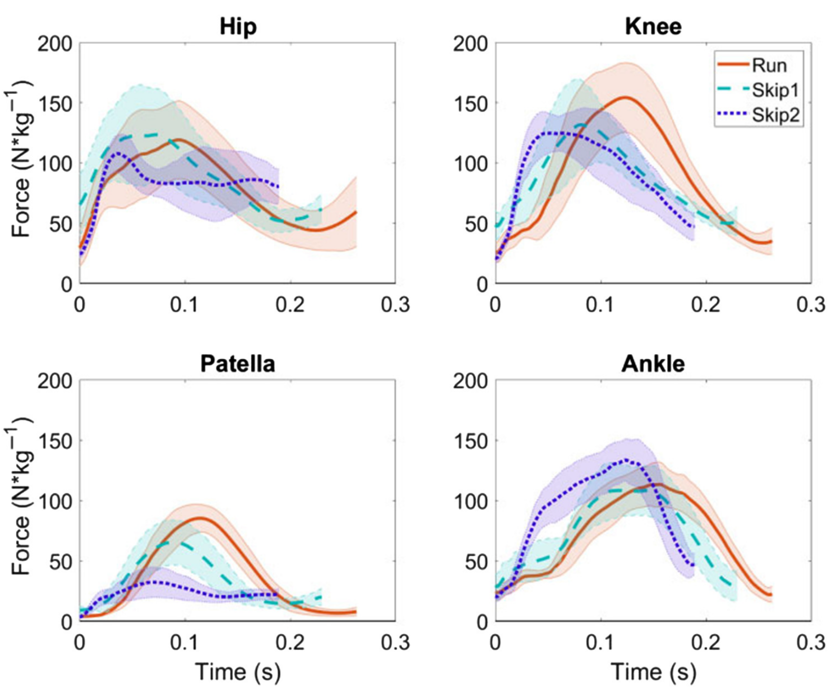

Figure 4 — Compressive joint contact forces during running and skipping steps during the stance phase. Thick lines represent the group mean, and the shaded area represents the SD.

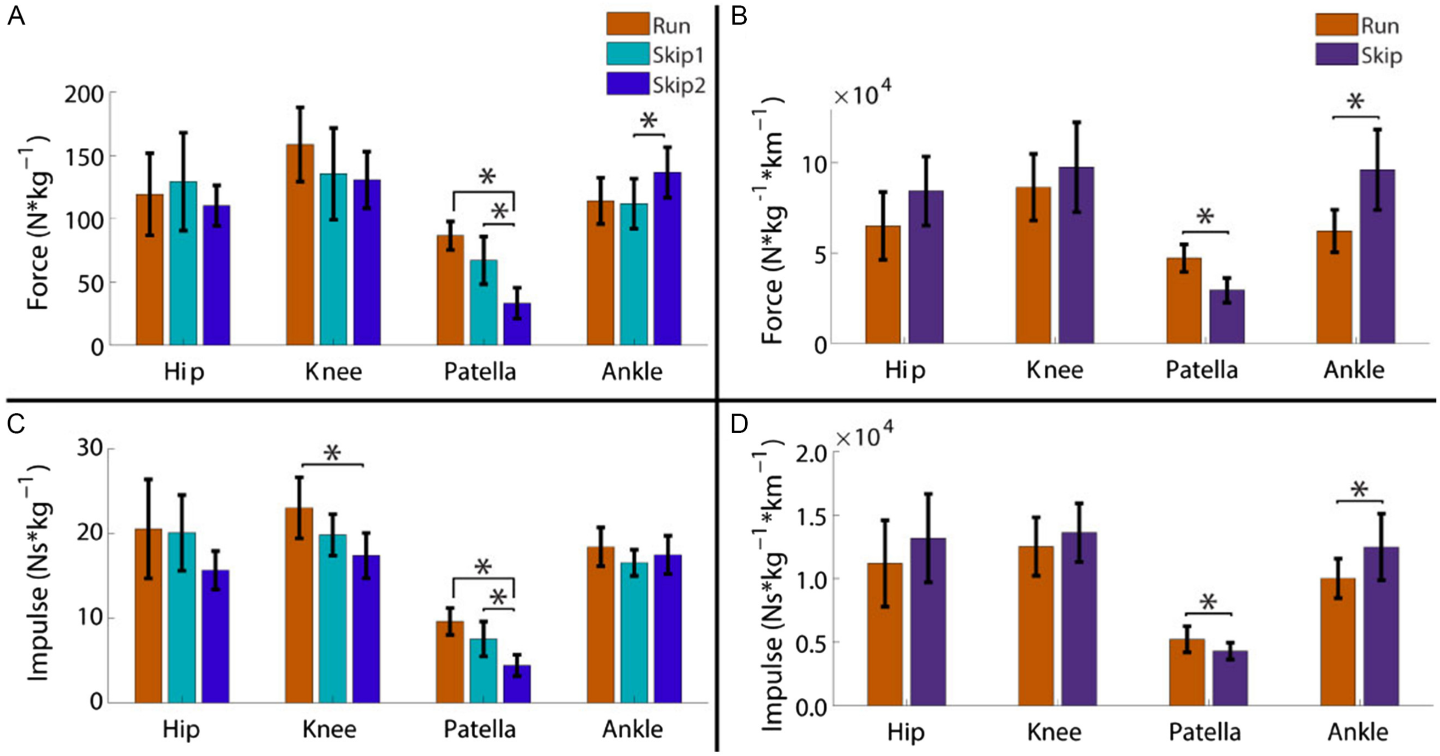

Figure 5 — Compressive joint contact force peaks and impulses during running and skipping. Bar heights represent the average, and error bars represent the SD of the peak force observed (A) per step and (B) per cycle normalized to distance traveled and the force impulse observed (C) per step and (D) per cycle normalized to distance traveled. * Statistically significant difference between steps or cycles ($P < .05$).

gaits. The results of this study support previous findings that found running has greater knee and patella joint contact forces than skipping[7] and that there is a greater energetic demand of the knee extensors (ie, VAS muscle group) in running compared with skipping. Furthermore, we found greater ankle joint contact forces during skipping than in running, which was accompanied by increased energetic demand from the uniarticular ankle plantarflexors (ie, SOL muscle group).

A single skipping cycle (comprised of 4 steps, 2 on each leg) required greater muscle energy expenditure than a running cycle (comprised of 2 steps, 1 on each leg). However, when normalized to the duration of a cycle (metabolic power) or the distance traveled over a cycle (cost of locomotion), only the SOL muscle group required greater metabolic power and cost of locomotion during the skipping cycle and there were no differences in whole-body metabolic power or cost of locomotion. Moreover, the VAS muscle group required greater metabolic power and cost of locomotion during the running cycle. Thus, the findings of this study do not fully explain the greater whole-body energy expenditure during skipping compared with running that has been observed in previous studies.[7,8] While the present study estimated energy expenditure based on a mathematical model of muscle energetics,[30] the previous studies measured whole-body metabolic energy expenditure by indirect calorimetry based on oxygen consumption during the last 1 to 2 minutes of exercise. An important distinction between these 2 methods is that the oxygen consumption measures ultimately reach a steady-state value that is measured at the end of the exercise bout, while the mathematical model of muscle energy expenditure is dependent on muscle activation which fluctuates throughout a gait cycle. Thus, the mathematical model used in this study does not provide an equivalent "steady-state" measure of muscle metabolic demand. In addition, the model used in this study includes limited upper body musculature (3 trunk muscles per side) and the arms are controlled by coordinate actuators which are not included in the metabolic cost calculation. It is possible that upper extremity muscles work more during skipping than running, but we were unable to capture these muscles' energy expenditure in our analysis. Still, the findings of this study suggest that relative muscle metabolic demand is specific to both the individual muscle and gait mode, which may have important implications on the susceptibility of specific muscle groups to fatigue. For example, the VAS may be more susceptible to fatigue during running while the SOL may be more susceptible to fatigue during skipping.

Regarding the muscle force impulses, an individual running step required greater force impulses from all muscle groups compared with one or both skipping steps. When these impulses were normalized to the distance traveled during a cycle, running still required greater force impulses from the TRUNK, GAS, and SOL muscle groups. A running cycle length is shorter than a skipping cycle (Table 2). Thus, running requires more cycles per kilometer than skipping, which would suggest differences in muscle impulses should be larger per kilometer than per step. However, since skipping requires 2 steps per leg per cycle, the sum of the muscle force impulses from skip 1 and skip 2 are often higher than the impulse during the run step, which reduces the differences per kilometer between cycles. These findings suggest that, for most muscle groups over a given distance, skipping requires similar muscle force impulse as running and similar muscle responses to routine participation in skipping and running may be expected.

The greater SOL force impulse per kilometer during running appears to contrast the lower SOL metabolic power and cost of locomotion observed in running compared with skipping. The

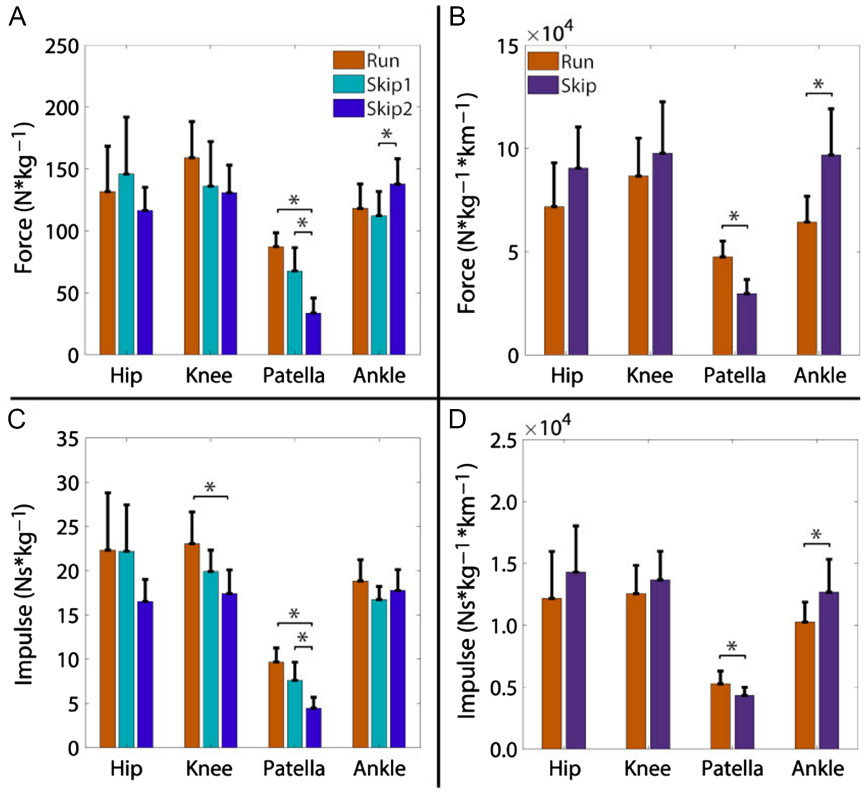

Figure 6 — Resultant joint contact forces and impulses during running and skipping. Peak resultant joint forces by (A) stride and (B) cycle per distance traveled. Peak resultant joint force impulses (C) stride and (D) cycle per distance traveled. * Statistically significant difference between cycles or strides ($P < .05$).

Table 2 Spatiotemporal Gait Parameters

Variable	Run	Skip 1	Skip 2
Step length,[*,a,b,c] m	0.92 (0.04)	0.62 (0.13)	0.78 (0.04)
Velocity,[*,c] $m \cdot s^{-1}$	2.57 (0.03)	1.48 (0.20)	5.81 (1.38)
Cadence,[c] $steps \cdot min^{-1}$	168 (8)	144 (16)	450 (127)
Contact time,[a,b,c] s	0.26 (0.02)	0.23 (0.02)	0.19 (0.01)
Vertical COM displacement—stance phase,[a,b] m	0.071 (0.004)	0.133 (0.026)	0.113 (0.025)
Cycle length,[d] m	1.84 (0.07)	2.78 (0.36)	
Cycle duration, s	0.72 (0.02)	1.13 (0.15)	
Vertical COM displacement—entire cycle,[d] m	0.090 (0.012)	0.184 (0.042)	

*Velocity of the simulated step was calculated as the step length divided by the step duration. Step duration was calculated as the time between consecutive right foot strikes. Step length was calculated as the displacement of the right heel marker between consecutive right foot strikes plus the product of the step duration and treadmill speed ($2.5\ m \cdot s^{-1}$).
Letters indicate pairwise differences ($P < .05$):
[a]Run and skip 1 steps. [b]Run and skip 2 steps. [c]Skip 1 and skip 2 steps. [d]Run and skip cycles.

estimate of muscle metabolic power is based on 3 primary variables[30]: the muscle's (1) activation and maintenance heat rate, (2) shortening and lengthening heat rate, and (3) mechanical work rate of the contractile element (wCE). A post hoc analysis was conducted to explore the contribution of each of these 3 variables to the cost of locomotion of the SOL in running and skipping (see Supplementary Material [available online] for full description of methods and results). Although there were no statistically significant differences between gaits for the 3 variables, wCE was greater in skipping than running for SOL. Moreover, the average SOL wCE during skipping was positive while during running it was negative, which suggests that the SOL muscle group performed greater eccentric activity during running but greater concentric activity during skipping. Thus, our findings of greater SOL metabolic power during skipping but greater force impulses during running are consistent with previous work demonstrating that eccentric muscle activity allows for the production of greater forces at a reduced metabolic cost.[33]

The range of peak hip, knee, and ankle compressive and resultant forces estimated in this study for running were consistent with those ranges previously reported for compressive[34,35] and resultant[36] forces during running. However, on average the tibiofemoral and patellofemoral compressive peak forces and impulses were greater than those previously observed in running and skipping steps.[7] Differences in the representation of the knee in the models in each study, the greater number of muscles included in the current study's model, and the methods for determining the muscle force contributions to joint contact forces may have contributed to these differences. Specifically, the CMC algorithm used to determine muscle forces in this study is known to estimate higher muscle forces than other techniques.[37] Still, the difference in peak tibiofemoral compressive forces between McDonnell et al[7] and the current study (36%) is consistent with differences between previous studies in the literature (29%) that report those forces.[34,35,38] Moreover, the relative trends between steps would be consistent, which provides confidence in the comparisons of joint contact force estimates between running and skipping.

The joint that incurred the most load differed between running and skipping steps and cycles. While the hip experienced similar joint loading in both gaits, greater knee and patella loads, where most running injuries occur, were observed during running, while skipping had greater ankle joint loading. The compressive joint contact forces contributed the most to the overall joint contact force. Thus, the greater compressive patella and ankle force peaks and impulses observed in running and skipping, respectively, translated to greater resultant patella and ankle force peaks and impulses in running and skipping, respectively. While skipping may reduce loading at the patellofemoral joint, the most common running-related injury site,[9] the ankle experiences increased loading compared with running. Thus, skipping may not be an appropriate cross-training exercise for athletes with a history of ankle injury (eg, previous Achilles tendon tears and ankle instability). However, future studies are required to determine whether this increased ankle loading in skipping poses a risk for injury and how individual mechanics (eg, rear-foot vs fore-foot striking) influence relative joint loading between running and skipping.

A potential limitation of this study was the small sample size which may have limited our ability to detect additional differences in measures of metabolic cost, muscle demand, and joint loading between running and skipping cycles. However, we detected the previously observed greater knee and patella joint contact forces in running as well as the novel finding of greater ankle joint contact forces in skipping. These observations were further supported by muscle-level differences identified between gaits. Still, given the large number of statistical tests that were performed in this exploratory study's assessment of individual muscle demand and multijoint loading, these results should be interpreted as provisional and provide promising directions for future hypotheses-driven studies comparing running and skipping.

In summary, skipping is an aerobically demanding exercise that has similarities to running in that it has some of the same elements: a single-limb stance and flight phase and high muscle and joint forces. However, running is associated with increased knee and patella joint loading and increased muscle demand, while skipping has greater ankle joint loading and muscle energetic demand. The findings of this study further support skipping as a viable alternative to running if the primary goal of the cross-training activity is to reduce joint loading at the commonly injured patellofemoral joint. However, the increased demand at the ankle during skipping should be noted from both a joint loading and muscle training perspective. These findings may help clinicians prescribe activities most appropriate for a patient's individual training or rehabilitation goals.

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