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Skipping has lower knee joint contact forces and higher metabolic cost compared to running

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ABSTRACT

Background: The health benefits of running based exercise programs are plentiful however the high rate of injury in these programs often reduces or eliminates exercise participation. Skipping has shorter steps, reduced vertical ground reaction forces (GRFs), and lower knee extensor torques, compared to running forming the basis of the present hypothesis that skipping would have lower tibio-femoral and patello-femoral joint contact forces.
Research question: The purpose of this study was to compare knee contact forces between skipping and running at the same speed. We also compared metabolic cost of these two gaits to examine the idea that the larger vertical displacement in skipping is a primary factor in its previously reported high metabolic cost.
Methods: The study evaluated joint contact forces through musculoskeletal modeling with GRF and 3D kinematic data and metabolic cost using oxygen consumption data from 20 young, healthy, trained participants as they skipped and ran on an instrumented treadmill at 2.68 m/s. Results: Skipping, compared to running, had substantially lower tibio-femoral and patello-femoral joint contact forces and linear impulses on both per-step and per-kilometer (i.e. lower cumulative loads) bases and also 30% higher metabolic cost. The lower joint loads in skipping were directly associated with its shorter steps and the higher metabolic cost was directly associated to its larger vertical displacement through the stride.
Significance: As joint loads may predispose individuals to running related injuries, skipping presents an attractive alternative exercise modality with additional increased aerobic benefits.

1. Introduction

Running has well documented health benefits and is an integral component to many athletic activities [1–3]. Participation in running can enhance performance capacity, providing that the participant is relatively injury-free. Unfortunately, the number of running-related injuries is on the rise, with 37–79% of runners annually reporting injury [4,5]. Lower extremity running injuries are often attributed to the inability of the lower extremity tissues to adequately control the loads applied throughout contact with the ground. High force loads are specifically cited as an indicator for injury [6–9]. While specific mechanisms of injury vary; it is known that running mechanics produce large ground reaction forces. These forces are propagated proximally with the line of action being dictated by the angular positions of the joints modifying moment arms and influencing the degree of torque acting upon each joint. These torques manifest as repetitive stress in ligaments, tendons, cartilage, and other connective tissue that act to stabilize associated joints [10–12]. Running exhibits high torques at the knee, escalating force produced by the quadriceps thus, increasing stress across the patellofemoral joint [13]. Excessive, repetitive stress with insufficient recovery time invariably leads to injury.

While the beneficial health outcomes that accompany running are substantive, as indicated above there is also an associated risk of injury. We therefore sought to investigate skipping as an alternative to running [14] based on studies finding skipping to possess reduced ground reaction forces [15] and higher metabolic demand [16] compared to running. Metabolic demand during locomotion is primarily a function of generating muscle force to support and accelerate the body's center of mass [17–20]. Overall, the metabolic cost of locomotion is proportional to the volume of active muscle and the rate of the force being generated [21]. Biomechanical factors that contribute to substantial variations in movement economy are: vertical oscillation, stride length, change in velocity at ground contact, and peak magnitude in vertical ground reaction forces [21]. Skipping exhibits substantial variations from running in these characteristics resulting in the strikingly high metabolic demand. Skipping utilizes shorter strides compared to

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running [14,16] which would be associated with lower muscle forces and metabolic cost [8,17,18,22]. Skipping, however also had a nearly two-fold larger vertical displacement, which we suspect is a primary cause of the comparatively larger cost of transport [16]. The comparatively greater metabolic demand of skipping is a substantial benefit for the individual looking to increase caloric expenditure [23]. We also reported a small yet significant reduction in maximum vertical GRFs with significant and substantial reductions in maximum knee joint extensor torques and the stance phase angular impulses compared to running [14]. Based on previous findings in the literature the shorter steps, reduced peak vertical GRF, and knee torques in skipping steps led us to hypothesize that skipping would have lower tibio-femoral and patello-femoral joint contact forces [24–27]. We tested this hypothesis in the present study, the purpose of which was to compare tibio-femoral and patello-femoral joint contact forces in skipping and running at the same speed. We also compared metabolic energy expenditure of these two gaits to verify previous results [16,28] and to examine the idea that the larger vertical displacement in skipping is a primary factor in its high metabolic expenditure.

2. Methods

The data reported here were derived from the tests and protocols described previously [14] thus we provide succinct descriptions of the methods described in the previous publication.

2.1. Participants & training

The study evaluated biomechanical data from 20 healthy, recreationally active participants (10 females). Selected participants were between the ages of 18 and 30 years (mean, sd: 21.5 ± 2.0 yrs), had a body mass index less than or equal to 28 kg/m^2 (Mean, sd: 23.3 ± 2.5 kg/m^2) and were able to complete the training program. The university institutional review board approved the protocol, and all participants provided written informed consent.

Participants were trained in skipping (a stepping pattern executed with a step and a hop on one leg followed by a step and a hop on the opposite leg repeated cyclically with alternating lead legs) on three separate days prior to a data collection including an initial over-ground, one mile skipping session partitioned into four skipping bouts. The subsequent two, one-mile training sessions were completed on a laboratory treadmill (Life Fitness 95 ti) to provide further skipping training and to acclimate to treadmill skipping so that accurate metabolic data could be collected. All participants reached the test speed for a minimum distance of ¼ and ½ mile over the final two training sessions. Upon completion of the training program participants had skipped a cumulative three miles and returned for a final session for metabolic and gait analysis. The entire program was completed within two weeks from informed consent to data collection.

2.2. Testing

Skipping and running trials were conducted in the East Carolina University Human Performance and Biomechanics Laboratories. Metabolic data (Truone 2400, Parvomedics, Sandy, UT) were collected first; a two minute standing calibration was obtained followed by a minimum of two minutes of walking to ensure the metabolic mask fitted properly. Participants proceeded with six minutes of running or skipping with the final two-minutes used to reflect a steady state movement. The order of running and skipping tasks was randomized across participants with a minimum of ten minutes rest between the two tests. We used the metabolic data to calculate metabolic energy expenditure in mL/kg//min (VO_2) and the cost of transport [28] which accounts for the metabolic demand above that of standing, and per unit distance.

A rest period in which participants were prepared for motion capture collection using a modified Helen Hayes marker set preceded the overground trials needed to collect the unilateral kinematic and kinetic data. Participants practiced running and skipping on the walkway to ensure that they would step on the force platform with the right foot without altering their gait pattern or target the force platform. Kinematic data were captured using Qualisys ProReflex MCU 240 cameras (Qualisys Medical AB, Gothenburg, Sweden) at 240 Hz. Ground reaction force data collected at a frequency of 960 Hz. were measured using an in-ground force platform (AMTI Model LG-6, Newton, Ma). An acceptable trial exhibited a consistent stride, unaltered to achieve complete foot fall on the force plate and within ±5% of 2.68 m/s. This speed was chosen through pilot work showing our sample could readily skip and run at this pace. Gait speed was regulated using infrared timing system (Brower timing systems, model IRD-T175, Salt Lake City, Utah).

A calibration trial was used to create an individualized unilateral linked rigid-segment system model for each participant. Joint centers were located by calculating fifty percent of the distance between the medial and lateral calibration markers for ankle and knee joints. The hip joint was calculated to be twenty-five percent of the distance between the markers identifying the right and left greater trochanters. Standard anthropometrics were used to locate each segment's center of mass from the proximal joint center [29]. Participants performed five successful trials for each condition: run and skip (lead foot contact, $skip_1$ and trail foot contact, $skip_2$). Condition order was randomized for each participant. We provide skipping and running videos in the online supplemental material for the reader to better understand the skipping motion.

2.3. Analysis

Net joint reaction forces and torques were calculated with inverse dynamics and Newton-Euler equations of motion with Visual 3D (C-Motion Inc., Rockville, Maryland, USA). We applied a biomechanical model predicting hamstrings, quadriceps, and gastrocnemius muscle forces, compressive tibio-femoral and patello-femoral joint contact forces and, shear tibio-femoral joint contact force. The model has been described extensively in previous studies [24,30,31] including all equations and has been often applied to running e.g. [24,27,32,33]. Subject-specific movement kinematics, joint reaction forces and torques, and standardized anthropometric and physiological data were entered into the model to calculate gastrocnemius, hamstrings, and quadriceps muscle forces and subsequently tibio-femoral compressive and shear forces and patello-femoral compressive force through the support phase. We accounted for any co-contraction of the hamstrings and gastrocnemius forces when calculating the quadriceps force [34]. The model was applied using proprietary software written by PD. Current predicted values for running were highly similar to those in the studies listed above.

We report the knee kinetic variables on a per step and per kilometer basis [27] because step lengths varied between running and both skipping steps [14]. The five-trial means across participants were calculated for selected kinematic and kinetic variables and entered into one of several statistical analyses. The primary knee kinetic variables for the per step analyses were entered into a one way, repeated measures, analysis of variance (ANOVA) to identify significant differences among the three gait steps (run, $skip_1$ and $skip_2$). Scheffe post hoc tests were used to determine specific differences in the case of a significant omnibus F-test. Since the cumulative load and metabolic analyses combined the two skipping steps, these variables were analyzed with dependent Student's T-tests. Alpha was set to 0.05 for all analyses.

3. Results

Knee joint contact forces and impulses were significantly higher on a per step basis in running compared to either skipping step with all

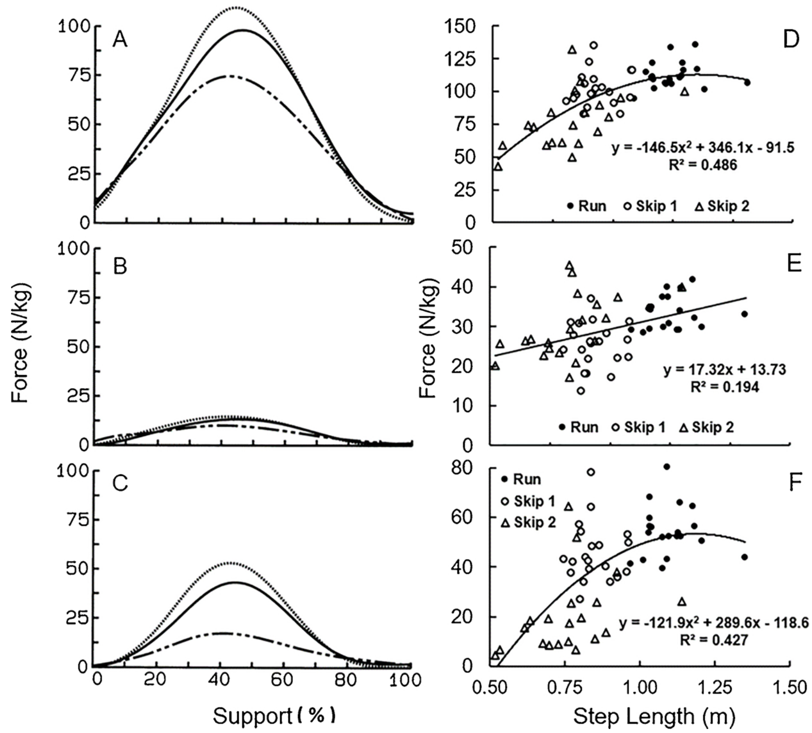

Fig. 1. Mean knee joint contact forces and their relationships with step length. A, D: tibiofemoral compressive force; B, E: tibio-femoral shear force; C, F: patello-femoral compressive force. Lines in A, B, C: solid: $Skip_1$, dashed: $Skip_2$, dotted: run.

Table 1
Mean (sd) knee joint forces on a per step basis for run and skip steps. Per kilometer comparison of knee forces and metabolic variables between running and skipping.

Variable		Mean (sd)		Mean Difference, 95% C.I. of Mean Difference		
Per step:	Run	$Skip_1$	$Skip_2$	Run v $Skip_1$	Run v $Skip_2$	$Skip_1$ v $Skip_2$
Peak tibio-femoral compressive force (N/kg)*	111 (±10) $^{\alpha\ \beta}$	101 (±13) $^{\gamma}$	77 (±22)	9.0, 2.4–17.5	33.9, 23.0–44.8	24.0, 12.5 – 35.6
Tibio-femoral compressive impulse (Ns/kg)*	15.3 (±1.6) $^{\alpha\ \beta}$	14.4 (±2.0) $^{\gamma}$	9.7 (±2.8)	1.0, −0.2–2.1	5.6, 4.2 – 7.1	4.7, 3.1 – 6.2
Peak tibio-femoral shear force (N/kg)*	33.4 (±41.) $^{\alpha\ \beta}$	25.1 (±5.8) $^{\gamma}$	29.7 (±8.1)	8.3, 5.0– 11.4	3.7, −0.4–7.8	4.5, 0.1 – 9.0
Tibio-femoral shear impulse (Ns/kg)*	4.38 (±0.65) $^{\alpha\ \beta}$	2.93 (±0.87) $^{\gamma}$	3.70 (±1.11)	1.44, 1.0–1.9	0.67, 0.09– 1.25	0.77, 0.13 – 1.41
Peak patello-femoral compressive force (N/kg)*	54.0 (±10.1) $^{\alpha\ \beta}$	45.4 (±11.8) $^{\gamma}$	19.9 (±15.6)	8.6, 1.6–15.6	34.1, 25.6 – 42.5	25.5, 16.6 – 34.3
Patello-femoral compressive impulse (Ns/kg)*	6.07 (±1.44) $^{\alpha\ \beta}$	5.07 (±1.60) $^{\gamma}$	2.16 (±1.58)	1.00, 0.02–1.97	3.91, 2.94 – 4.88	2.91, 1.89 –3.93

Per kilometer:	Run	Skip	Run v Skip
Peak tibio-femoral compressive force (N/kg/km)	50,891 (±5154)	50,440 (±5301)	–
Tibio-femoral compressive impulse (Ns/kg/km)	6988 (±842)	6756 (±779)	–
Peak tibio-femoral shear force (N/kg/km)	15,185 (±2026)	15,325 (±2350)	–
Tibio-femoral shear impulse (Ns/kg/km)#	1994 (±330)	1853 (±376)	141, −85–367
Peak patello-femoral compressive force (N/kg/km)#	24,691 (±4983)	18,187 (±5174)	6,504, 3257–9,750
Patello-femoral compressive impulse (Ns/kg/km)#	2778 (±715)	2015 (±608)	763, 339–1,187
Metabolic energy expenditure (VO_2 in ml/kg/min)#	31.6 (±3.4)	41.1 (±2.5)	9.5, 7.5–11.4
Cost of Transport (J/(kgm))#	3.34 (±0.40)	4.56 (±0.34)	1.22, 0.98– 1.46

comparisons between all steps being statistically significant ($p < 0.05$) [Fig. 1 and Table 1]. Peak tibio-femoral compression force and the linear impulse of this force were on average, 8% and 51% higher in running compared to $skip_1$ and $skip_2$ steps, respectively. Peak tibio-femoral shear force and the linear impulse of this force were on average, 15% and 41% higher in running compared to $skip_2$ and $skip_1$ steps (shearing forces were higher in $skip_2$ vs $skip_1$). Lastly, peak patello-femoral compression force and the linear impulse of this force were on average, 20% and 276% higher in running compared to $skip_1$ and $skip_2$ steps. Peak compression forces at the tibio-femoral and patello-femoral joints were positively and strongly correlated with step length with correlation coefficients of $r = 0.69$ and 0.65 respectively, $p < 0.05$. Peak tibio-femoral shear force was also positively correlated with step length, although not as strongly with $r = 0.44$, $p < 0.05$.

Mean (sd) step lengths were 1.10 (0.17), 0.85 (0.07), and 0.76 (0.14) m for running, $skip_1$ and $skip_2$ with all values being significantly different from each other ($p < 0.05$) and resulting in 910 and 1139 steps per kilometer in running and skipping. On a per kilometer basis (i.e. the cumulative load) tibio-femoral peak force and linear impulse and peak tibio-femoral shear force were statistically identical between running and skipping. Tibio-femoral shear impulse was however 8% higher and peak patello-femoral force and linear impulses were on average 37% higher in running compared to skipping (all $p < 0.05$). Overall, running had substantially larger peak forces and linear impulses compared to skipping on both single step and cumulative load bases.

Metabolic energy expenditure of skipping was 30% higher than that of running and the cost of transport was 37% higher in skipping compared to running, both $p < 0.05$. Both variables were strongly associated with vertical displacement through the stride (Fig. 2). Neither

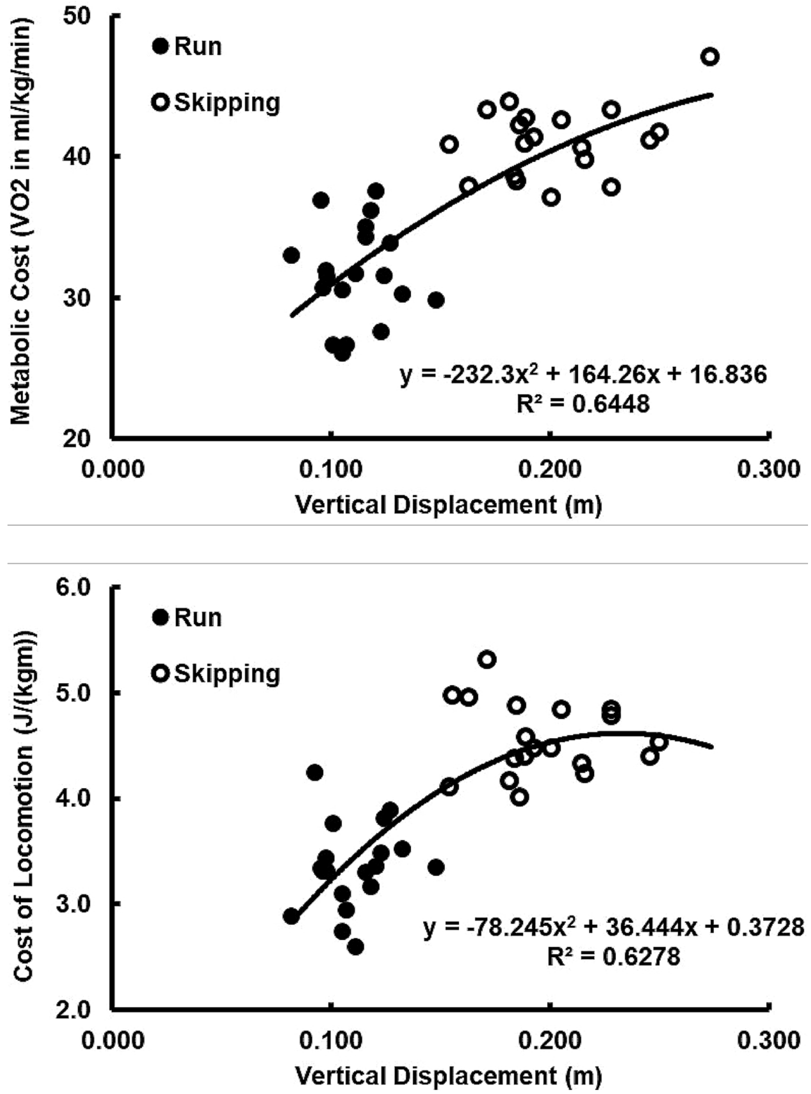

Fig. 2. Relationships between metabolic cost and cost of locomotion with vertical displacement in running and skipping.

variable however was correlated with step length for skipping and running respectively (data not shown).

4. Discussion

Lower extremity injuries are often attributed to lower extremity tissues being unable to adequately attenuate the applied loads throughout contact with the ground [4,10]. Repetitively imparted high loads are specifically cited as an indicator for injury [9,35,36]. Skipping displayed significantly lower peak compressive forces and impulses than running at both the tibiofemoral and patellofemoral surfaces. While self-selected speed may be slower in skipping compared to running, participants performed both gaits at the identical speed of 2.68 m/s. This single test speed, chosen based on pilot work showing that the participants could readily skip and run at this pace, may limit the generalizability of the results and is slower than that of the average runner as typically seen in the biomechanics literature (e.g. 3.0 m/s, Messier et al [32]). Importantly however, the single, moderate speed assured that differences between gaits were not due to differences in speed.

Decreased knee joint contact forces were positively correlated with a decreased step length (Fig. 1) which, in turn is inversely correlated with stride rate [27,37]. Hamill and Derrick have separately shown that step length affects the level of shock imparted on the lower extremity with decreased step length (or increased step rate) being associated with decreased impact force peaks [7,27]. Lenhart et al. and Chumanov et al. both demonstrated shorter steps had lower peak patellar tendon force throughout stance [38,39]. Willson et al showed reduced patellofemoral contact force [27] and stress [40] and reduced tibio-femoral compression [24] with shorter steps. Through a probabilistic stress fracture model, Edwards et al. [41] demonstrated that shorter steps reduced the probability of having a tibial stress fracture. The running step was 37% longer than the average of the two skipping steps (i.e. 0.30 m longer) which is much larger than the approximately 5%–10% step length differences in the literature cited here. We observed on average 30% higher peak and impulse tibiofemoral loads and 98% higher peak and impulse patello-femoral loads in running compared to skipping. These differences are larger than those reported in this cited literature which averaged about 10% between running conditions of different step lengths. We consider the present differences as substantial and largely due to differences in step length, but also due to fundamentally different gait biomechanics between running and skipping [14,16]. We point out that all participants took longer running steps compared to either of the skipping steps. It is also important to note that our maximum tibio-femoral (11.3 BWs) and patello-femoral compressive forces (5.50 BWs) during running were very similar to the average of the cited studies, i.e., 10.4 BWs and 5.33 BWs, respectively.

The two shorter steps comprising the skip stride necessitate a 25%

increase in number of steps taken per unit distance traversed (i.e. 229 more steps per km). Despite the reduced joint forces and impulses calculated on a per-step basis, the larger number of skipping steps may act to counteract the per-step differences [42]. Indeed, tibio-femoral compression force and impulse as well as peak tibio-femoral shear force were equalized between skipping and running in the cumulative analysis. Tibio-femoral shear impulse and both patello-femoral variables however, remained higher in running in the cumulative analysis. We propose that the evidence strongly indicates that the skipping gait has substantially lower knee joint loads in each step compared to running and these reductions are generally maintained over distances typically run (e.g. several km). The lower knee joint contact forces in skipping compared to running on both per step and per km bases is relevant, as some reports approximate nearly half of all running related injuries occur at the knee with an estimated half of those involving the patellofemoral joint [8,43]. Then, as previously discussed [6–1014,39–41], if peak knee joint contact forces or impulses are causal factors in overuse, running-related injuries, the substitution of some amount of running with an equal distance or equal duration of skipping may enable runners to reduce their injury potential at the knee. It is worth noting that no research has explored injury potential in skipping and thus in reducing risk at the knee. It is also possible that skipping may shift loads to other structures, e.g. the Achilles tendon, another common injury site. In this case, skipping may not be advisable for runners with Achilles tendinopathy.

Measures of metabolic cost represent energy usage and can be used as a benchmark for cardiovascular and musculoskeletal benefits obtainable with a particular activity [16,23,44]. Skipping utilized 30% more calories compared to running at the same speed which equates to an additional 236 kcal/hour. The cost of transport showed skipping to be 37% more costly than running, per unit distance. For the same unit time or distance, skipping can provide significantly greater aerobic benefits compared to running. The increase in oxygen and caloric consumption in skipping compared to running may be explained by the differences in work done on the center of mass, in particular accelerating the mass to a larger magnitude in the vertical direction. The cost of performing work on a body's center of mass, redirecting and accelerating it, comprises 45% of the net metabolic cost during locomotion [17,18]. It follows that locomotion patterns with larger vertical displacement will also have a greater demand for oxygen which we demonstrated in Fig. 2. The change in vertical position was nearly double in skipping versus running as observed previously [16]. This change in position was strongly correlated to both metabolic measures. We did not control vertical kinematics and all participants self-selected their vertical displacements in both gaits. Despite this self-selection, all participants had greater vertical displacement in skipping without exception. Additionally, the training program completed prior to testing entailed skipping a minimum of three miles, reducing the novelty of the task and each participant had enough experience to adopt a comfortable technique [45,46]. While it is possible that further skipping practice would reduce the difference in the metabolic cost between skipping and running, we note that Minetti et al. also reported skipping to be up to 30% more metabolically costly than running [28]. Their participants were described as experienced at skipping on treadmills. We do note that within each gait technique, the correlations were weak (skipping) or non-existent (running). However, we view these data as a generalized locomotion phenomenon depicting the strong relationship between vertical displacement and metabolic demand across gaits.

The substantially different mechanisms of ground contact between the three steps and particularly the two skipping steps led to much greater variability in knee joint loads in skip_2 compared to skip_1 and running steps. The large variability was most evident in the peak forces and linear impulses at both tibio-femoral and patello-femoral joints. Skip_2 followed the flight phase with the large vertical displacement whereas Skip_1 contacted the floor as a walking step with the contralateral foot also in contact with the floor (please see supplemental videos). Also, skip_2 had much larger and more rapidly applied posterior GRF than both other steps due in part to the high horizontal velocity produced by skip_1 [14]. Apparently, the larger variability in skip_2 measures reflects the greater difficulty in controlling the lower extremity in the more impulsive or impactful floor contact phase following the large vertical descent and high horizontal velocity. It is also possible that increased variability is a function of the relative novelty of the task and may be reduced with further practice. We also highlight the interesting outcome that while the force and impulse variabilities were relatively high in skip_2, the magnitudes of these forces and impulses were the lowest of all three steps.

5. Conclusion

We previously showed that skipping, compared to running, had shorter steps, lower maximum vertical GRF, and reduced knee extensor torque [14] leading us to hypothesize that skipping would have lower tibio-femoral and patello-femoral joint contact forces. The data presented in this paper confirmed this hypothesis for young, healthy adults skipping and running at 2.68 m/s. Skipping, compared to running, had substantially lower tibio-femoral and patello-femoral joint contact forces and impulses on both per-step and per-kilometer bases. The lower joint loads in skipping were positively associated with the shorter steps in this gait. As these factors may predispose individuals to running related injuries at the knee, skipping presents and attractive alternative with additional increased aerobic benefits. Certainly, running is an integral component of many athletic activities and as such run training can enable people to better perform these activities. We suggest however that incorporating an amount of skipping into a training regimen may be beneficial to those suffering from or who are at risk of running related knee injuries [47]. The additional benefit of higher rates of oxygen consumption and caloric expenditure due to the larger vertical displacement in skipping allows an individual to exercise for less time or distance while maintaining the same aerobic and health benefits and in this case, potential decrease risks of knee injury.

Conflict of interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.03.028.

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