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COMPARISON OF JOINT KINETICS DURING FREE WEIGHT AND FLYWHEEL RESISTANCE EXERCISE

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ABSTRACT. Chiu, L.Z.F., and G.J. Salem. Comparison of joint kinetics during free weight and flywheel resistance exercise. *J. Strength Cond. Res. 20(3):555–562. 2006.*—The most common modality for resistance exercise is free weight resistance. Alternative methods of providing external resistance have been investigated, in particular for use in microgravity environments such as space flight. One alternative modality is flywheel inertial resistance, which generates resistance as a function of the mass, distribution of mass, and angular acceleration of the flywheel. The purpose of this investigation was to characterize net joint kinetics of multijoint exercises performed with a flywheel inertial resistance device in comparison to free weights. Eleven trained men and women performed the front squat, lunge, and push press on separate days with free weight or flywheel resistance, while instrumented for biomechanical analysis. Front squats performed with flywheel resistance required greater contribution of the hip and ankle, and less contribution of the knee, compared to free weight. Push presses performed with flywheel resistance had similar impulse requirements at the knee compared to free weight, but greater impulse requirement at the hip and ankle. As used in this investigation, flywheel inertial resistance increases the demand on the hip extensors and ankle plantarflexors and decreases the mechanical demand on the knee extensors for lower extremity exercises such as the front squat and lunge. Exercises involving dynamic lower and upper extremity actions, such as the push press, may benefit from flywheel inertial resistance, due to the increased mechanical demand on the knee extensors.

KEY WORDS. power, impulse, microgravity, exercise countermeasures

INTRODUCTION

Traditional free weight exercise utilizes resistance provided by gravitational force to impose a stimulus on the musculoskeletal system. Over the past decade, alternative means of providing resistance have been studied, particularly in evaluating the role of resistance exercise for space flight. The most common alternative resistive sources include flywheel inertial devices and elastic resistance devices (1–3, 13, 16). Flywheel inertial devices provide a source of linear resistance from a spinning disc with considerable mass attached to a tether acting at a distance from the axis of rotation. Mechanically, the inertial torque is a function of the mass of the disc, the disc's radius of gyration, and the disc's angular acceleration (18). The linear resistance force is the product of the flywheel disc's inertial torque multiplied by the perpendicular distance of the tether to the center of the disc.

Previous investigators have employed flywheel inertial devices to study the function of skeletal muscle as relates to the production of force and performing mechanical work, as well as to evaluate muscular strength and power (14, 15). These devices fall under the broad category of accommodating resistances, where the resistive force is dynamic and proportional to the force generated by the individual. As an individual applies greater force to the tether, the angular acceleration of the disc increases, which subsequently increases the resistive force on the tether (15).

A potential benefit of flywheel inertial devices is that the resistance is independent of gravity. As such, resistance can be applied from any direction, not simply vertical, and resistance can be applied in situations with reduced gravity, such as space flight. Previously, Berg and Tesch (3) have described a flywheel inertial device and reported the forces generated during a leg press exercise. This report did not, however, quantify the mechanical demand at individual joints during the exercise, and no comparison has been made between exercises performed with flywheel inertial vs. free weight resistances. In addition to studying the magnitude of mechanical demand, the temporal component is also of interest as flywheel inertial resistance is not constant throughout the exercise range of motion. In the case of the flywheel inertial device, where resistance is proportional to the force applied, an increase in applied force from an increased mechanical advantage is accompanied by an increase in resistance. This difference may manifest when considering the impulse or area under the net joint moment (NJM)-time curve. The purpose of this investigation is to compare lower extremity joint kinetics for exercises performed using free weight vs. flywheel inertial resistance.

METHODS

Experimental Approach to the Problem

This study utilized a randomized cross-over design to compare individuals performing the same exercises with different sources of resistance. The exercises performed were the front squat (Figure 1), lunge (Figure 2), and push press (Figure 3), and the resistance sources were free weight (barbell) and flywheel inertial. Following 2 practice sessions, subjects participated in 2 testing sessions. In each session, subjects performed all 3 exercises but only using 1 resistance source—the other resistance source was used on the second session. The actual order of testing sessions was randomized.

Subjects

Men ($n = 5$) and women ($n = 6$) voluntarily participated in the investigation subsequent to providing informed consent as approved by the University of Southern California Health Sciences Institutional Review Board. A sample size of 11 subjects allows detection of effect size

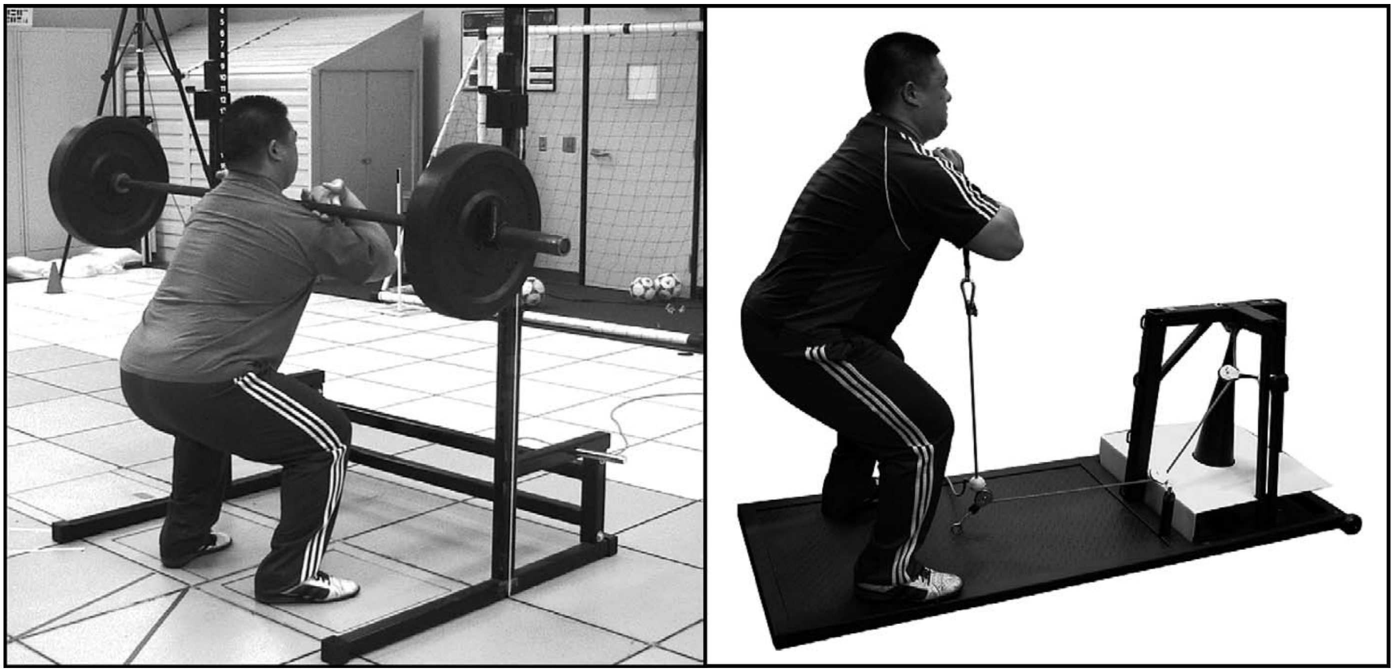

FIGURE 1. Free weight (left) and flywheel (right) front squat.

differences of magnitude 0.5 (moderate difference) while minimizing type 1 error to 1% and type 2 error to 10% (power = 90%) (12).

Prior to data collection, all subjects had participated in a free weight training program involving the lower extremity for at least the previous 6 months. Subject characteristics are presented in Table 1. Subjects performed 2 practice sessions where the front squat, lunge, and push press exercises were performed using both resistance sources. During the second practice session, subjects' 5 repetition maximum (RM) was determined for the free weight exercises.

Procedures

Following a brief warm-up, subjects performed each exercise for 3 sets of 3 repetitions, either with free weights or the flywheel inertial resistance. For free weights, the load was the subjects' 5RM. For the flywheel inertial resistance, the moment arm was set at level 5 (squat) or level 4 (lunge, push press), where level 1 is the least resistance and level 5 is the greatest resistance. An interset rest interval of 2–3 minutes was provided to allow recovery and minimize fatigue.

The flywheel inertial device (VersaPulley; Heart Rate Inc., Costa Mesa, CA) consists of a flywheel with two 1-kg masses positioned at opposite ends of metal beam with a length of 0.48 m. A fixed axis is located at the center of the beam, about which the masses rotate. A cone is attached above the flywheel, and as the flywheel and cone spin, a tether winds and unwinds around the cone. As the tether unwinds, the length of the tether increases (concentric movement). When the tether completely unwinds,

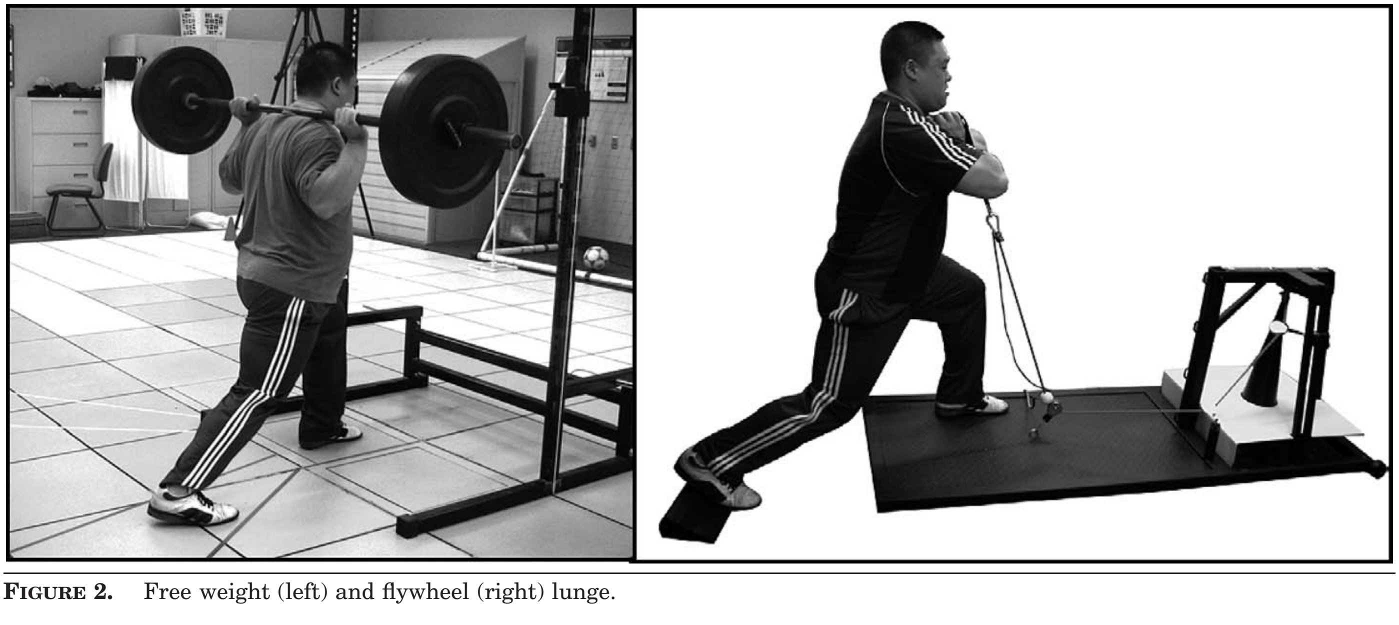

FIGURE 2. Free weight (left) and flywheel (right) lunge.

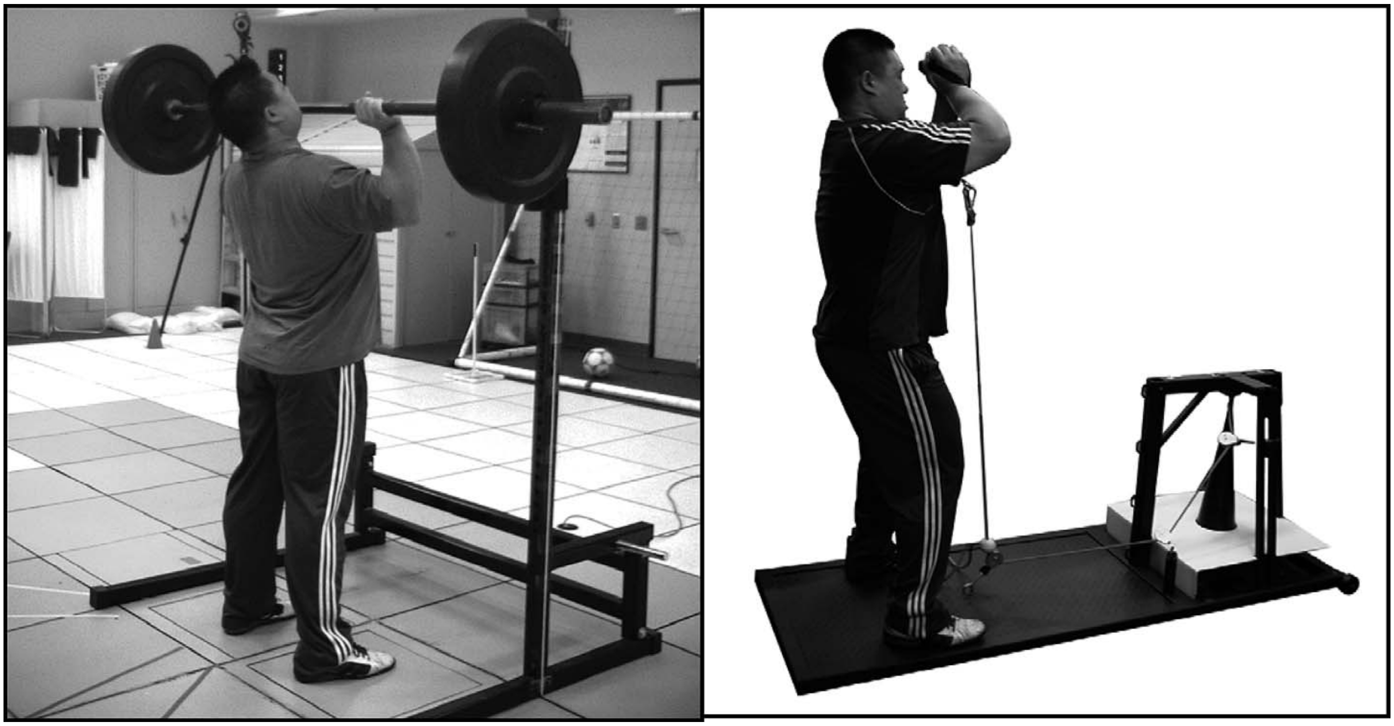

FIGURE 3. Free weight (left) and flywheel (right) push press.

TABLE 1. Subject characteristics.*

	Mean ± *SD*	Range
Height (m)	1.72 ± 0.08	1.57–1.88
Body mass (kg)	77.25 ± 21.01	56.59–126.14
Front squat 5RM (kg)	69.55 ± 28.49	38.64–143.18
Lunge 5RM (kg)	58.14 ± 17.15	34.09–79.55
Push press 5RM (kg)	48.86 ± 21.08	29.55–93.18

* RM = repetition maximum.

the cone continues to spin and the tether begins to wind around the cone (eccentric movement).

Motion Analysis

For testing sessions, exercises were performed standing on force platforms (AMTI, Watertown, MA). During the squat and push press, subjects stood on 2 force platforms, while during the lunge, only the forward leg was on a force platform. Reflective markers on the subjects' body were recorded using an 8-camera optoelectronic motion capture system (Vicon 612; Vicon Peak, Lake Forest, CA). Analog data were collected at 1,560 Hz and low-pass filtered at 20 Hz. Video data were collected at 120 Hz and low-passed filtered at 6 Hz.

A six degree of freedom marker set, which included calibration and tracking markers, was placed on the subject (10). Calibration markers were placed on important bony structures to determine proximal and distal segment ends in relation to the tracking markers. Tracking markers consisted of 3 (foot) or 4 (shank, thigh) reflective markers mounted on rigid plastic frames. The same investigator placed markers on each subject for all sessions. Test-retest reliability of joint angle and moment data using these procedures is high (intraclass correlation >0.90). A single static calibration trial was performed to locate the tracking markers relative to the calibration markers. For dynamic trials of exercise performance, only tracking markers remained on the body.

Collected trials were processed in Vicon Workstation (version 4.5; Vicon, Los Angeles, CA), where markers were labeled and saved in .c3d file format. The .c3d files were imported into Visual 3D (version 3.13; C-Motion, Rockville, MD), which modeled segment characteristics from static trials and generated body segment kinematics from dynamic trials. Inverse dynamics, using published anthropometric data, were applied for 3 planes of motion to determine NJM at the ankle, knee, and hip (10, 15).

At the ankle, knee, and hip, frontal and transverse plane net joint kinetics were small; therefore, only sagittal plane kinetics were considered. To generate net joint power (NJP), angular displacement and NJM data were smoothed using a 13-point moving average smoothing technique (4). The area under the NJM-time curve was integrated to calculate impulse (IMP). Data parameters of interest were average NJM, average NJP, and IMP. All joint kinetic data are presented as internal moments normalized to body mass. Data were analyzed in absolute and relative terms. Joint kinetics were analyzed in relative terms to determine the contribution of a given joint to the total mechanical demand of the lower extremity. Joint demand distribution profiles were calculated for average NJM, average NJP, and IMP. For each measure, hip, knee, and ankle joint kinetics were summed, and the joint kinetics at each joint were expressed as a percentage of the summed total (9). The summed total is similar to the support moment described by Winter (8, 17). Resultant ground reaction force was determined from force platform data.

Statistical Analyses

As data for left and right limbs were not different, joint kinetics and ground reaction force data were averaged for

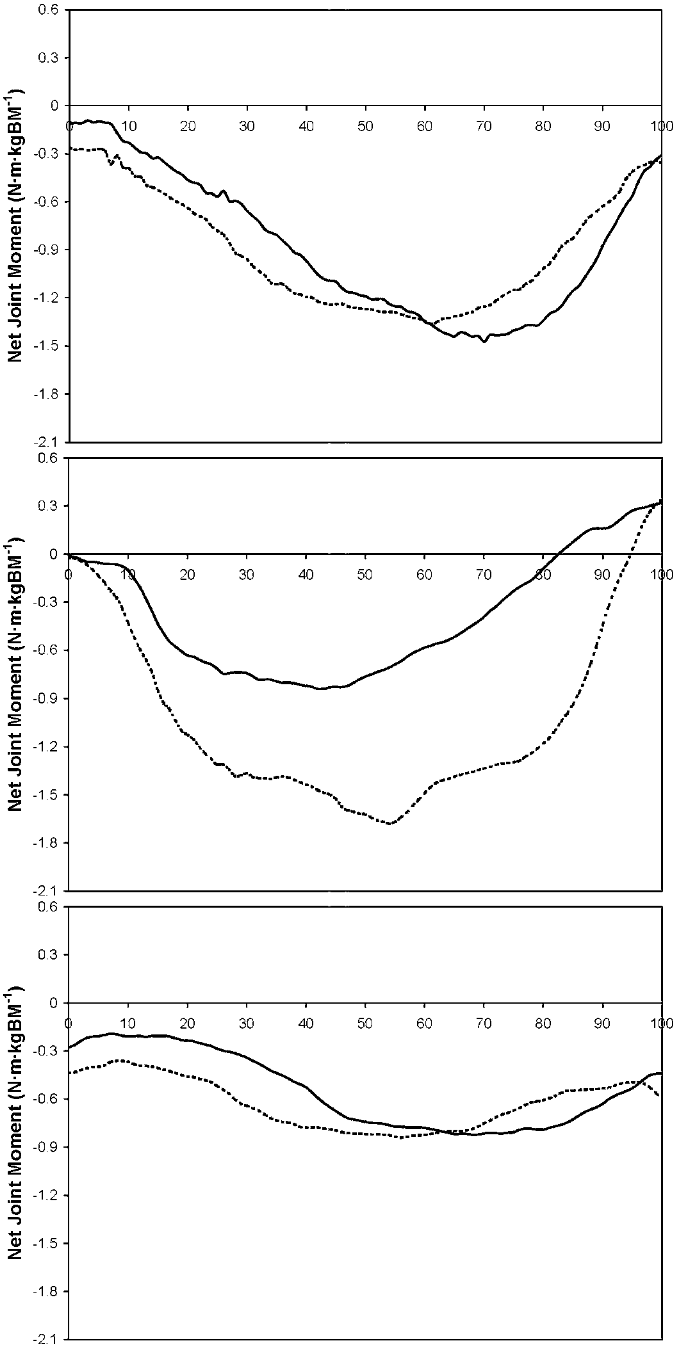

FIGURE 4. Net joint moment for hip (top), knee (middle), and ankle (bottom) during flywheel (solid line) and free weight (dashed line) front squat. Time is normalized to 0–100% of squat cycle starting with eccentric phase. Negative moment indicates extensor or plantarflexor.

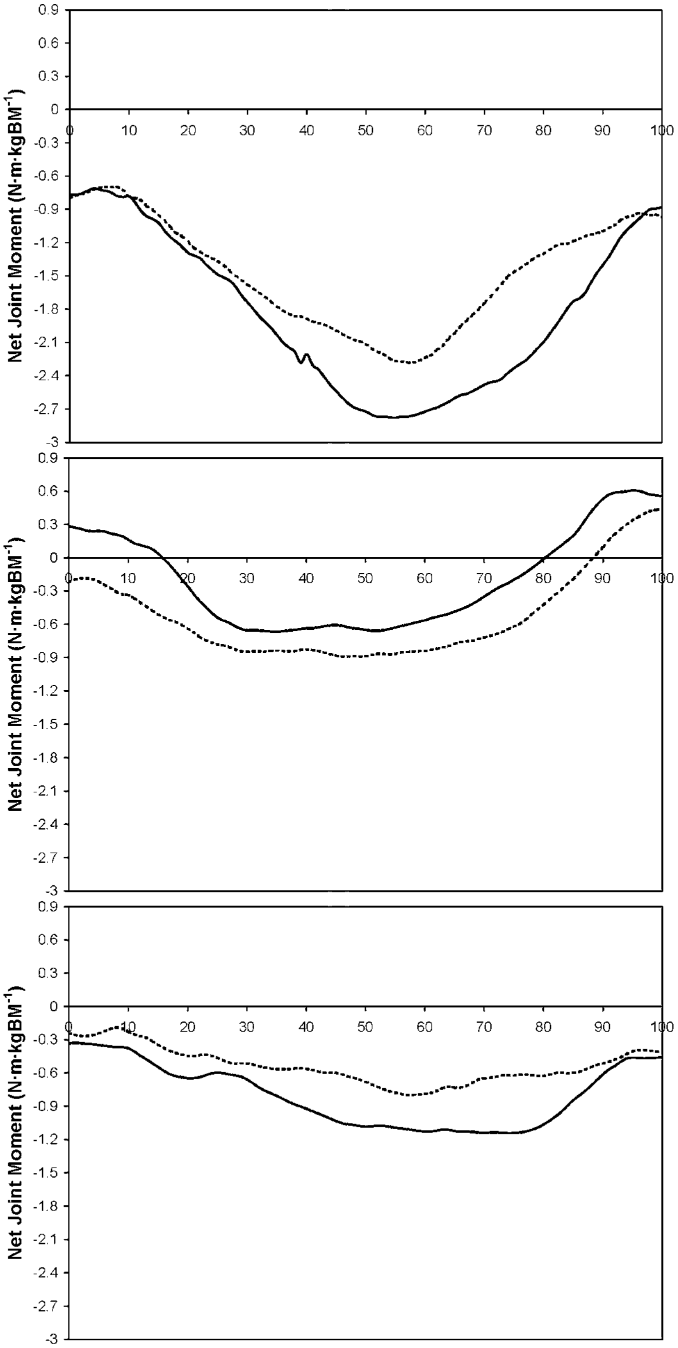

FIGURE 5. Net joint moment for hip (top), knee (middle), and ankle (bottom) during flywheel (solid line) and free weight (dashed line) lunge. Time is normalized to 0–100% of lunge cycle starting with eccentric phase. Negative moment indicates extensor or plantarflexor.

data analysis. All statistical analyses were performed in SPSS (version 11.5; SPSS, Inc., Chicago, IL). Statistical significance was tested using one-way (resistance source) repeated measures multivariate analysis of variance (ANOVA). Three levels were used for each multivariate analysis—hip sagittal plane, knee sagittal plane, and ankle sagittal plane. When the multivariate ANOVA was significant, post-hoc univariate ANOVA determined at which level the differences existed. Ground reaction forces were compared using paired-sample *t*-tests. Magnitude of differences was determined as eta-squared (η^2; multivariate ANOVA) and Cohen's *d* (univariate ANOVA; *t*-test). Statistical significance was accepted at $p \leq 0.05$.

RESULTS

Ensemble average NJM-time curves are presented in Figure 4 (front squat), Figure 5 (lunge), and Figure 6 (push press). Statistically significant differences for IMP (Table 2) existed for the front squat ($p = 0.004$; $\eta^2 = 0.84$), lunge ($p = 0.003$; $\eta^2 = 0.82$), and push press ($p < 0.001$; $\eta^2 =$

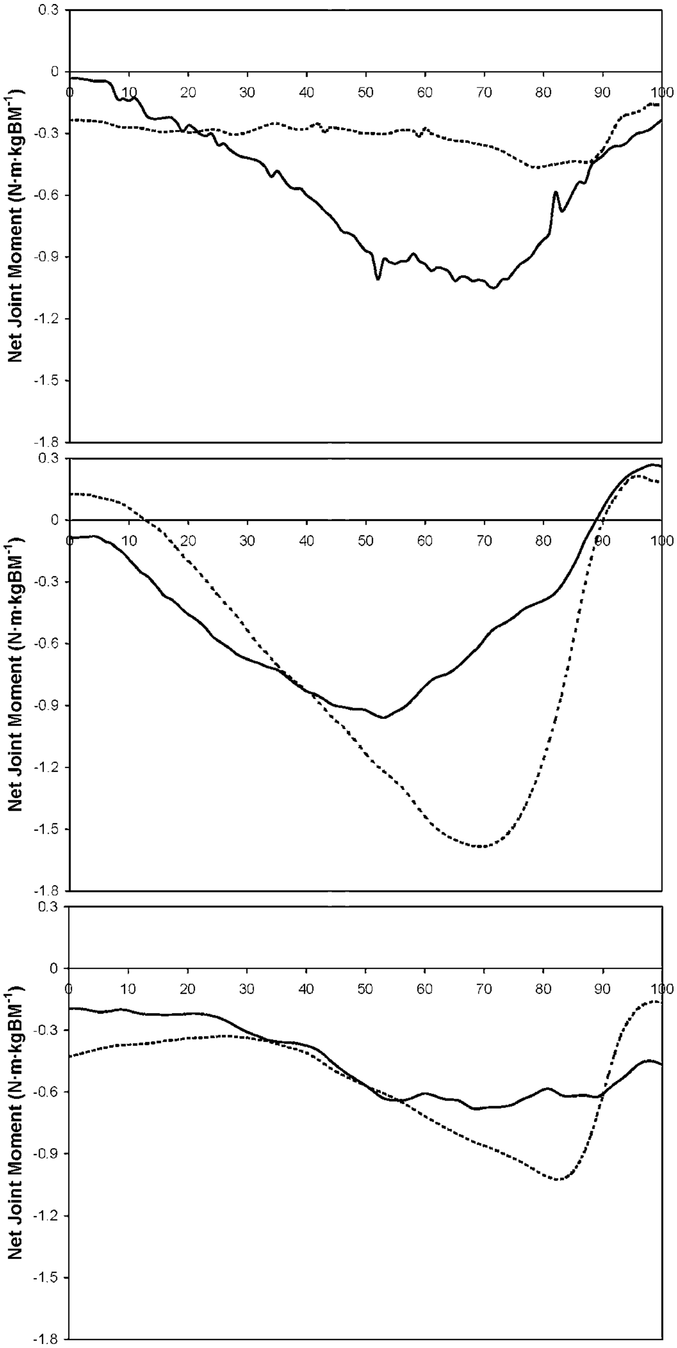

FIGURE 6. Net joint moment for hip (top), knee (middle), and ankle (bottom) during flywheel (solid line) and free weight (dashed line) push press. Time is normalized to 0–100% of push press cycle starting with eccentric phase. Negative moment indicates extensor or plantarflexor.

0.84). For the front squat, only the IMP at the knee joint was different, with the free weight condition larger than the flywheel condition ($p = 0.002$; $d = 2.54$). For the lunge, IMP was moderately smaller at the knee ($p = 0.007$; $d = 1.39$) and moderately larger at the ankle ($p = 0.04$; $d = 0.90$) for the flywheel condition vs. the free weight condition. For the push press, IMP was larger at the hip ($p < 0.001$; $d = 2.52$) and ankle ($p = 0.001$; $d = 2.42$) joints during flywheel exercise. Similar differences between conditions existed for average NJM (Table 3) and average NJP (Table 4).

The IMP demand distribution for the front squat differed between free weight and flywheel conditions ($p < 0.001$; $\eta^2 = 0.82$; Figure 7). The contribution of the hip ($p = 0.006$), knee ($p < 0.001$) and ankle ($p = 0.005$) were significantly different between conditions, with the hip ($d = 1.53$) and ankle ($d = 2.08$) contributing more for the flywheel front squat and the knee ($d = 2.69$) contributing more for the free weight front squat. The same pattern was seen for the NJM demand distribution ($p = 0.001$; $\eta^2 = 0.82$) and NJP demand distribution ($p < 0.000$; $\eta^2 = 0.90$).

A moderately significant multivariate difference existed for the IMP demand distribution for the lunge ($p = 0.002$; $\eta^2 = 0.75$; Figure 8). The IMP contribution from the knee was moderately smaller during the flywheel lunge compared to the free weight lunge ($p = 0.003$; $d = 1.41$). The contribution from the ankle was larger during the flywheel lunge ($p = 0.002$; $d = 2.07$). A significant difference also existed for the NJM demand distribution ($p = 0.03$; $\eta^2 = 0.53$), but not the NJP demand distribution ($p = 0.66$; $\eta^2 = 0.09$). Only the ankle contribution to the NJM demand was significantly different between conditions ($p = 0.01$; $d = 1.29$).

The IMP demand distribution was significantly different for the push press ($p = 0.001$; $\eta^2 = 0.84$; Figure 9). The contribution of the hip ($p < 0.001$; $d = 2.46$) was larger for the flywheel push press, whereas the contribution of the knee ($p < 0.001$; $d = 2.41$) was larger for the free weight push press. A moderate but nonsignificant multivariate difference existed for the NJM demand for the push press ($p = 0.10$; $\eta^2 = 0.40$). The moderate difference for hip NJM demand approached significance ($p = 0.09$; $d = 0.84$), where hip NJM contributed more for the flywheel push press than the free weight push press. Knee NJM contributed more to the NJM demand for the free weight push press than the flywheel push press ($p = 0.05$; $d = 0.90$). The NJP demand distribution was significantly different between conditions ($p = 0.001$; $\eta^2 = 0.81$). Similar to the IMP and NJM demand distribution, the hip ($p = 0.001$; $d = 2.10$) contributed more to the NJP demand for the flywheel push press while the knee ($p < 0.001$; $d = 2.63$) contributed more for the free weight push press.

The peak resultant ground reaction force was larger

TABLE 2. Net joint impulse normalized to body mass ($N{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}kg^{-1}$) (mean ± *SD*).

	Front squat		Lunge		Push press	
	Free weight	Flywheel	Free weight	Flywheel	Free weight	Flywheel
Hip	−301 ± 154	−278 ± 59	−446 ± 220	−448 ± 83	−40 ± 50	−166 ± 50*
Knee	−335 ± 124	−120 ± 46*	−144 ± 81	−62 ± 37*	−104 ± 31	−118 ± 37
Ankle	−190 ± 70	−175 ± 27	−158 ± 64	−204 ± 39*	−71 ± 22	−139 ± 35*

* Significantly different ($p < 0.05$) than free weight.

TABLE 3. Average net joint moment normalized to body mass ($\text{N}\cdot\text{m}^{-1}\cdot\text{kg}^{-1}$) (mean ± *SD*).

	Front squat		Lunge		Push press	
	Free weight	Flywheel	Free weight	Flywheel	Free weight	Flywheel
Hip	−0.917 ± 0.398	−0.988 ± 0.235	−1.632 ± 0.647	−1.893 ± 0.391	−0.264 ± 0.395	−0.660 ± 0.204*
Knee	−1.172 ± 0.090	−0.446 ± 0.147*	−0.519 ± 0.349	−0.229 ± 0.234*	−0.796 ± 0.383	−0.529 ± 0.106
Ankle	−0.574 ± 0.167	−0.614 ± 0.064	−0.573 ± 0.211	−0.850 ± 0.156*	−0.599 ± 0.238	−0.547 ± 0.095

* Significantly different ($p < 0.05$) than free weight.

TABLE 4. Average net joint power normalized to body mass ($\text{W}\cdot\text{kg}^{-1}$) (mean ± *SD*).

	Front squat		Lunge		Push press	
	Free weight	Flywheel	Free weight	Flywheel	Free weight	Flywheel
Hip	0.801 ± 0.426	1.641 ± 0.425	1.191 ± 0.441	2.479 ± 0.571*	0.871 ± 1.216	1.567 ± 0.490
Knee	1.513 ± 1.070	0.251 ± 0.321*	0.418 ± 0.339	0.025 ± 0.341*	2.513 ± 1.318	0.559 ± 0.230*
Ankle	0.252 ± 0.102	0.398 ± 0.114*	0.247 ± 0.154	0.432 ± 0.128*	2.090 ± 1.188	0.757 ± 0.283*

* Significantly different ($p < 0.05$) than free weight.

for the free weight front squat ($p = 0.002$; $d = 1.29$) and free weight push press ($p = 0.001$; $d = 1.50$) compared to the exercises performed using the flywheel inertial device. Conversely, peak resultant ground reaction force was not significantly different between the free weight and flywheel lunge ($p = 0.62$; $d = 0.15$).

DISCUSSION

There are clear differences in the relative contribution of the hip, knee, and ankle joints in the sagittal plane to the total IMP, NJM, and NJP demand when comparing exercises performed with free weights vs. a flywheel inertial resistance device. The greatest differences in the distribution of IMP, NJM, and NJP occurred for the front squat and push press exercises. A general pattern was apparent for both of these exercises where the hip musculature contributed more to the total moment and power demand when performed with the flywheel inertial resistance device. In contrast, the knee musculature contributed more for the exercises with free weights. For the front squat exercise, the ankle is also seen to contribute more to the total demand for exercises with the flywheel inertial resistance.

For the front squat exercise, the differences in the relative contributions from the hip and knee were large for the IMP, NJM, and NJP. However, the push press at the hip and knee exhibited large differences for the IMP and NJP demand distributions but only moderate differences for the NJM demand. The push press exercise utilizes less external resistance than the front squat; therefore, the total NJM demand for the lower extremity is likely to be lower. It is possible that the differences between exercises will not be apparent when considering the NJM alone (8). Rather, because the push press is a power exercise, joint angular velocity is also a consideration. Thus, NJP, the product of the NJM and joint angular velocity, may be a superior parameter for assessing differences between power-type exercises. As IMP is the integral of the NJM with respect to time, IMP may also be a better parameter than NJM for power-type exercises.

The differences in absolute IMP demand between exercise modalities were not the same for the front squat and push press. For the front squat, the absolute IMP was similar at the hip and ankle joints for the free weight and flywheel modalities; however, the IMP at the knee was larger for the free weight condition. Therefore, the free weight front squat with a 5RM load appears to provide a greater overload for the knee extensor musculature compared to the flywheel inertial device as used in this investigation.

For the push press, the absolute IMP at the knee was similar for both conditions. The absolute IMPs at the hip and ankle were larger for the flywheel condition. This suggests that for the push press exercise, a greater de-

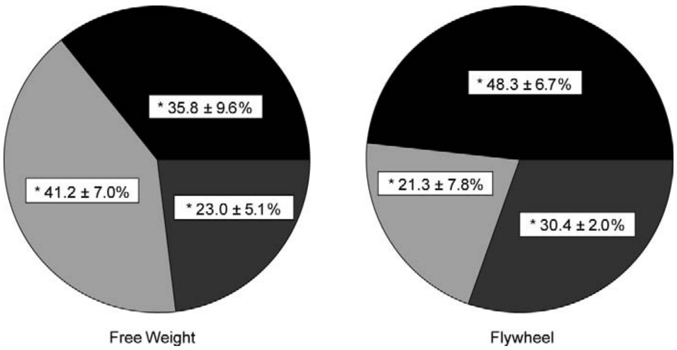

FIGURE 7. Relative impulse demand distribution for the front squat. Black = hip extensor; light gray = knee extensor; dark gray = plantarflexor. *Significant difference free weight vs. flywheel ($p < 0.01$).

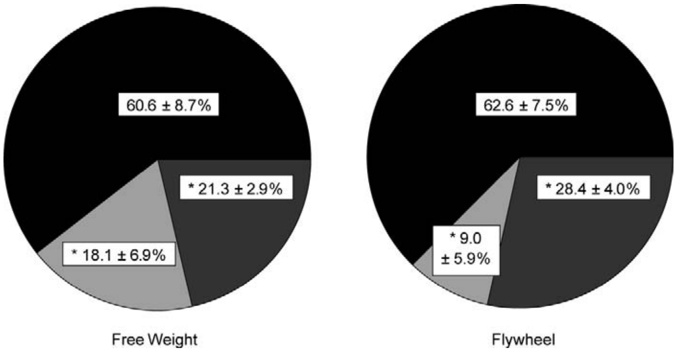

FIGURE 8. Relative impulse demand distribution for the lunge. Black = hip extensor; light gray = knee extensor; dark gray = plantarflexor. *Significant difference free weight vs. flywheel ($p < 0.01$).

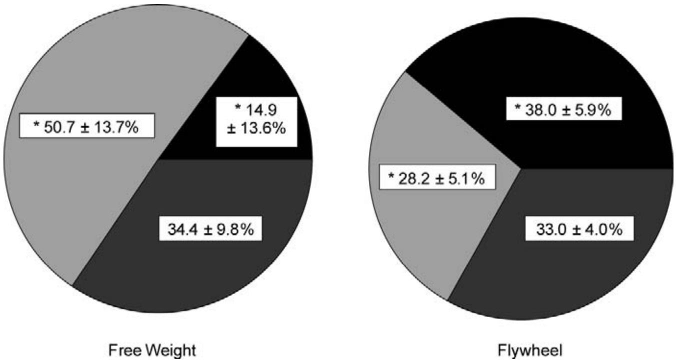

FIGURE 9. Relative impulse demand distribution for the push press. Black = hip extensor; light gray = knee extensor; dark gray = plantarflexor. *Significant difference free weight vs. flywheel ($p < 0.01$).

mand is placed on the hip extensor and ankle plantarflexor musculature using the flywheel inertial device rather than free weights with a 5RM load. Both modalities place similar demand on the knee extensor muscles for this exercise.

Interestingly, despite differences in the relative distribution of IMP, NJM, and NJP across lower extremity joints for the front squat and push press exercises, the exercise modality did not largely affect the relative distributions for the lunge. For both modalities, the largest relative contribution to the IMP, NJM, and NJP demand came from the hip extensor musculature. The contribution from the ankle was greater than for the knee for both modalities, although the contribution of these joints was small compared to the hip. The absolute IMP demand for the lunge was similar between exercise modalities. Absolute IMP at the hip was large for both modalities. The absolute IMP was greater at the knee for the free weight modality but greater at the ankle for the flywheel modality. For both conditions, the IMPs at the knee and ankle are small relative to the hip. Typically, when instructing an individual to perform the lunge exercise, the shank is maintained in a near vertical position while the femur descends until it is approximately parallel to the ground (7). In considering the free body diagram for the leading limb, the moment arm for the vertical forces is large for the femur and small for the shank, thus the NJM and IMP are expected to be large at the hip and small at the knee. Regardless of whether free weight or flywheel inertial resistance is used, the lunge exercise appears to place a large demand on the hip extensor musculature.

The large mechanical demands placed on the lower extremity musculature appear within reasonable limits compared to other heavy resistance exercise (11). Anecdotally, there is concern over the potential for injury from flywheel resistance as a result of a large rate of eccentric loading. The rate of loading, however, appears to be dependent on the exercise and joint (see Figures 4–6). During the front squat, the rate of increase for the knee extensor NJM is greater for the free weight condition. However, the rate of increase for the knee extensor NJM during the push press is greater for the flywheel condition. Other common exercises in strength and conditioning have large eccentric loading rates, such as vertical jump landings and the catch phase of the power clean (4). None of the subjects in the current investigation had muscle strains or joint pain performing flywheel exercise. Further long-term investigation is required to determine if flywheel resistance has greater potential for injury than free weight exercise.

Previous investigations with alternative resistances, such as elastic materials, have demonstrated an inability to stimulate bone mineral adaptation despite increases in muscular strength (16). Stimulation of positive bone mineral adaptations using alternative resistances has been studied in regard to exercise countermeasures for space flight. A limitation of elastic resistance is Hook's law, where force is directly proportional to length change. Thus, for an exercise like the squat, resistance is lowest at maximal flexion and greatest during maximal extension. Exercise against elastic resistance has been found to elicit ground reaction forces lower than those found with free weights (13). Large ground reaction forces have been considered an important characteristic for stimulating positive bone mineral adaptations, in particular, during space flight (6). Flywheel inertial resistance is directly proportional to applied force; thus, resistance is at the momentary maximum at any given point in the range of motion. This large resistance can result in large ground reaction forces comparable to those during free weight exercise, as demonstrated in this investigation for the lunge. This exercise modality has been shown to be effective at maintaining muscle strength and power (1), although future investigations are required to determine its effectiveness for stimulating bone mineral adaptations and the potential role of flywheel inertial resistance in microgravity (2).

PRACTICAL APPLICATIONS

Flywheel inertial resistance exercise requires mechanical demand most suited for exercises involving dynamic lower and upper extremity actions. Exercises, such as the push press, may benefit from utilizing flywheel resistance. This exercise modality as used in this investigation, however, reduces loading on the knee extensor musculature during lower extremity only exercise; thus, it may not be appropriate for development of maximal strength of the knee extensors in comparison to free weight training. The use of flywheel inertial resistance should be investigated for microgravity situations, in particular, the effectiveness of such exercise to maintain or enhance muscular strength and power and bone density.

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