Foot-Ground Reaction Force During Resistance Exercise in Parabolic Flight

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Running Title: Resistance Exercise and Microgravity

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Stuart -
My comments are in red and initialed "DLF"

-Dan

- A nice paper that shows what ya'all thought from the start!

ABSTRACT

INTRODUCTION: An interim Resistance Exercise Device (iRED) was designed to provide resistive exercise as a countermeasure to space flight-induced loss of muscle strength and endurance as well as decreased bone mineral density. The purpose of this project was to compare foot-ground reaction force during iRED exercise in normal gravity (1-g) versus microgravity (0-g) achieved during parabolic flight. METHODS: Four subjects performed three exercises using the iRED (squat, heel raise, and deadlift) during 1-g and 0-g at a moderate intensity (60% of maximum strength during deadlift exercise). Foot-ground reaction force was measured in three axes (x,y,z) using a force plate, and the magnitude of the resultant force vector was calculated ($r = \sqrt{x^2 + y^2 + z^2}$). Range of motion (ROM) was measured using a linear encoder. Peak force (PkF) and total work (TW) were calculated using a customized computer program. Paired t-tests were used to test if significant differences ($p \leq 0.05$) were observed between 1-g and 0-g exercise. RESULTS: PkF and TW measured in the resultant axis were significantly less in 0-g for each of the exercises tested. During 0-g, PkF was 42-46% and TW was 33-37% of that measured during 1-g. ROM and average time to complete each repetition were not different from 1-g to 0-g. CONCLUSIONS: When performing exercises in which body mass is a portion of the resistance during 1-g, PkF and TW measured during resistive exercise were reduced approximately 60-70% during 0-g. Thus, a resistive exercise device during 0-g will be required to provided higher resistances to induce a similar training stimulus to that on Earth.

INTRODUCTION

Prolonged exposure to microgravity (0-g) results in a loss of muscle mass (12), reduced muscle strength and endurance (8,14,21), and decreased bone mineral density (18,19). These changes occur primarily in those regions of the body, the legs and the trunk, that are involved in locomotion and maintenance of an upright posture (6,11,13) in normal gravity (1-g). As a result, space flight-deconditioned crewmembers may be less able to complete strenuous tasks, such as extravehicular activity or post-flight emergency egress from the Space Shuttle (5, 10) or may be at increased risk for injury during and after space flight (2). Further, the time to recover from the adverse effects of space flight would be hypothesized to be greater if no countermeasures were performed.

Resistive exercise has been suggested to be a countermeasure to musculoskeletal deconditioning during 0-g (2,3,4,5,6,8). Therefore, in preparation for long duration stays of three months or greater aboard the International Space Station (ISS), several resistive exercise devices were considered as a complement to the planned treadmill and cycle ergometer. Potential resistive exercise devices had to be of limited mass, volume, and power consumption because volume and power are limited commodities aboard ISS. Further, because crew time is severely constrained by routine ISS operations, the resistive exercise device would have to be easy to deploy, operate, and stow. The resistive exercise device also would have to provide high loads (up to 2675 N; 600 lbs.) for a variety of exercises based upon preliminary long-duration bed rest studies (17).

A resistive exercise device was developed, but because of the limited space and power available on ISS prior to assembly complete, this device could not meet the requirements of an ideal resistive exercise device for exercise in 0-g and therefore was considered an interim resistance exercise device (iRED; Figure 1). The iRED was designed to fit in Node 1 of ISS (the passageway between segments), to remain partially deployed when not in use, and to require no power to operate. The iRED provides resistance to the user as the user pulls a cord from the base of the unit. As the cord is pulled outward, it rotates a series of elastomer-spoked wheels, called FlexPacks, which exert a force when they are deformed as they resist rotation. Due to design limitations of the hardware, the force development of the iRED was limited to 1337 N (300 lbs.), and the maximal linear motion was limited to 59 cm (22 in) at resistances greater than 936 N (210 lbs.). Pilot data from our laboratory suggested that the foot-ground reaction force curve for this device appears to be different from traditional isotonic, or dynamic constant external resistance (DCER), exercise. Although these limitations of the hardware were noted, the hardware was accepted for initial use aboard ISS until more advanced concepts could be developed and implemented.

Insert Figure 1 Here

The purpose of this project was to better understand the expected loads placed upon the body during iRED exercise in 0-g, as would be experienced by crewmembers during space flight. Therefore, we measured the foot-ground reaction force during iRED exercise in 0-g induced by parabolic flight. We examined the three main exercises prescribed during long-duration missions, squat, deadlift, and heel raise, to better understand how to properly prescribe resistive exercise using the iRED. Specifically, we hypothesized that the peak force (PkF) and total work (TW) measured at the foot-ground interface would be significantly less in 0-g compared to 1-g at the same load setting. Further, we sought to determine whether differences between 1-g and 0-g PkF could be accounted for by subtracting the static force of body mass from the measure of PkF in 1-g. That is, we hypothesized that the PkF measured during 1-g exercise without the static force of body mass would be similar to the PkF measured during 0-g exercise. This is the first study to examine the effect of 0-g exposure on foot-ground reaction forces during resistive exercise.

METHODS

Subjects

Four male test subjects (29.8±7.6 yr; 177.8±13.5 cm; 91.5±18.1 kg) experienced with exercise using the iRED volunteered to participate in this project. All subjects completed a modified Air Force Class III physical examination and were screened for history of orthopedic or musculoskeletal disorders. Subjects received verbal and written explanation of the potential risks and benefits of the testing protocol. Subjects signed a consent form indicating voluntary participation. Testing procedures were reviewed and approved by the NASA-Johnson Space Center Committee for the Protection of Human Subjects.

Testing Protocol

Prior to participation in the testing protocol, subjects received a familiarization session in the laboratory during which the project objectives and tasks were fully explained. Subjects performed the three exercises of interest, squat, deadlift, and heel raises, on the iRED. The approximate maximal strength, one repetition maximum (1-RM), was determined for the deadlift exercise. One subject had their 1-RM recently tested as part of a training study in our laboratory (15), and three subjects self-determined their 1-RM as part of their normal resistive exercise training routine. Approximately 60% of the deadlift exercise 1-RM was used for subsequent testing for each exercise during both normal and 0-g. This was required to minimize set-up time between exercises during the parabolic flight and to maximize time available for data collection during each 20-25 sec parabola.

On the day of testing, each subject reported to the NASA JSC Reduced Gravity Office at Ellington Field, TX. Testing hardware was set-up and calibrated on an aircraft specifically modified for parabolic flight (KC-135). Prior to flight, each subject performed at least three sets of 6 repetitions of each exercise at approximately 60% of their deadlift 1-RM. During parabolic flight, subjects attempted to complete the same number of sets and repetitions at the same resistance setting on the iRED as during 1-g. One subject was tested during each of four flights (four subjects, four flights). One test operator served as a safety spotter during all exercises, and two other test operators were responsible for data collection.

For squat and heel raise exercises, subjects donned a set of modified football shoulder pads. From the outer portion of these pads, a cable was attached to a pulley system to which the cord from the iRED was attached. For deadlift exercise, the iRED cables were attached directly to the ends of a short, shoulder-width bar designed for use with the iRED. Both the shoulder pads and the deadlift bar were similar to the hardware used during ISS missions. All exercises started in the upright, standing position.

Foot-ground reaction forces were measured using a force plate (Model z15540, Kistler Instrument Corporation, Amherst, NY) placed between the iRED canisters, and range of motion was measured using a linear encoder (Model PV-50, Patriot Sensors and Control Corporation, Semi Valley, CA) placed in parallel to one of the iRED cables. The force plate was oriented such that the positive z-axis represented the direction from the head to the feet of the subject, the positive x-axis was directed from the subject forward, and the positive y-axis was oriented from the subject to his left. Force was measured in the x, y, and z-axes, and the magnitude of the resultant force vector was calculated as $r = \sqrt{x^2 + y^2 + z^2}$. Force and range of motion data were recorded (LabView Version 4.0, National Instrument Corporation, Austin, TX) for later analysis. The force plate and linear encoder were calibrated prior to each flight.

A customized computer program calculated the PkF, TW, range of motion (ROM), and time to complete a repetition for each repetition in each set of exercise. PkF was accepted as the highest measured force in each repetition. TW for each repetition was calculated by using numerical integration to determine the total area under the force and displacement curves. ROM was measured as the linear difference between the starting point and ending point of the exercise in each repetition. Time to complete a repetition was calculated as the time for the exercising subject to move through the entire ROM and return to the start point of the exercise.

Data Analysis

Due to the short duration of each parabola, subjects were not able to perform as many repetitions during 0-g as they performed prior to flight. Therefore, we selected only the initial data (sets and repetitions) collected during 1-g to compare to data collected during 0-g. In this way, equal numbers of sets and repetitions were analyzed in both gravity conditions. For the deadlift exercise, the first five repetitions from three sets of exercise were compared between the 1-g and 0-g conditions. For the heel raise exercise, data from the first eight repetitions from four sets were compared. For the squat exercise, data from the first six repetitions from three sets were compared.

Within each set of exercise, the PkF in each axis, TW per repetition measured in the resultant force vector, ROM, and time to complete each repetition were averaged. Mean PkF, TW per repetition, ROM, and time per repetition were compared between 1-g and 0-g conditions using paired t-tests. Also, we determined whether differences in PkF from 1-g to 0-g could be accounted for by removing the static force of body mass in the z-axis and compared these values to those obtained during 0-g. The PkF measured in the z-axis minus body mass was averaged for each exercise set in 1-g and compared to PkF from parabolic flight using paired t-tests. Significance was determined *a priori* at $p \leq 0.05$.

RESULTS

The PkF observed in the z-axis (Table 1) and the resultant vector (Figure 2) were significantly less in 0-g than in 1-g for all exercises. The PkF during the squat exercise in 0-g in the z-axis was 41±2% and in the resultant vector was 42±2% of that in 1-g. The mean PkF during the deadlift exercise during 0-g in the z-axis and in the resultant vector was 43±1% of that observed during 1-g. Similarly, the PkF during the heel raise exercise in 0-g in the z-axis was 46±1% and for the resultant vector was 45±2% of that in 1-g.

Insert Table 1 Here
Insert Figure 2 Here

There were no significant differences in PkF between 1-g and 0-g in the x- or y-axis during the squat (Table 1). However, during deadlifts PkF in the x-axis was positive in 0-g compared to negative in 1-g, and during heel raises PkF in the Y-axis was significantly less negative in 0-g than in 1-g.

Similar to PkF, TW was significantly greater in 1-g compared to 0-g (Figure 3). TW during squat exercise in 0-g was 33±2%, during deadlift was 35±1%, and during heel raise was 37±2% of the TW performed during 1-g.

Insert Figure 3 Here

The mean ROM was not different for any exercise from 1-g to 0-g (Table 2). There also was no difference in the mean time to complete each repetition between the two conditions.

Insert Table 2 Here

PkF measured in the z-axis minus the static force of body mass for 1-g was significantly greater than PkF for 0-g (Figure 4). PkF measured in 0-g were 86±4% during squat exercise, 85±2% during deadlifts, and 93±2% during heel raises of that measured during 1-g exercise minus static body mass.

Insert Figure 4 HERE

DISCUSSION

iRED Exercise as a Countermeasure During Microgravity

This was the first study to directly measure the foot-ground reaction forces during resistive exercise in a 0-g environment and directly compare the results to the same exercise in 1-g. As expected, the major finding of this study was that the foot-ground reaction force and TW were significantly less during exercise in 0-g than during 1-g. In addition, the reduction in PkF was not entirely explained by an effect of reduced gravity acting on the static body mass. These results indicate that exercise hardware design for 0-g should include provision for heavier resistances than expected to replicate the PkF and TW that the body experiences in 1-g resistive exercise. For example, a 75 kg (165 lbs.) crewmember who can perform a near maximal squat with 1471 N (330 lbs.) of resistance in 1-g may be able to perform the same exercise in 0-g with a resistance in excess of 2207 N (495 lbs.).

In our experience from previous evaluations during parabolic flight, subjects have reported that they could perform resistive exercises with substantially more resistance in 0-g than in 1-g. This would be expected because the subject would not be experiencing the force of gravity on the mass of his own body during 0-g exercise. As a point of comparison to the iRED, the typical untrained male can perform a supine leg press with resistances of 980 N to 1960 N (220 to 440 lbs.) for normal exercise training (Tesch, 1997). Because the supine leg press in 1-g and squat exercise in 0-g may be considered similar due to the lack of body mass as a component of the total resistive load, these data suggest that astronauts might be expected to exceed the capabilities of the iRED (1337 N; 300 lb.) since resistive exercise is a normal component of the prescribed pre- and in-flight exercise training. Therefore, the current peak load of the iRED may be sub-optimal for training the lower body strength during 0-g because crewmembers may not be able to exercise with sufficiently high resistances.

you don't really train "the lower body strength". You train the lower body with the goal of maintaining or increasing strength. DLF

To further elucidate this issue, we examined data collected in our laboratory during a bed rest study, as an analogue of space flight, and from a recent training study. Subjects who performed supine resistive exercise every other day during a 14-day bed rest trained at average resistances of approximately 1628-1736 N (365-389 lbs.) during leg press exercise (4) and 1697-1814 N (381-407 lbs.) during heel raise exercise (3). These subjects had not participated in resistive training for at least one year prior to the study. Further, subjects who performed no exercise training during the bed rest were able to exert an average of 2040 N (458 lbs.) of force during a supine DCER leg press (4) and 1922 N (431 lbs.) during supine DCER heel raise exercise (3) after deconditioning. In our training study (15), untrained subjects completed 1-RM lifts during the squat exercise of 981 N (220 lbs.) and during the heel raise exercise of 1579 N (354 lbs.). Based upon their average body mass (82 kg; 180 lbs.) and an assumed training intensity of 80-90% 1-RM, these subjects would be training at loads in excess of 1589-1687 N (356-378 lbs.) for the squat and 2069-2226 N (464-499 lbs.) for heel raises. Therefore, the maximum desired resistance for the a resistive exercise device may be in excess of 2942 N (700 lbs.) or higher to protect against muscle deconditioning in some astronauts.

As a temporary solution to this problem, ISS crewmembers have the option to augment force provided by the iRED by attaching elastic cords (three parallel strands of surgical tubing in each) in parallel with the iRED cable. In our experience in a training study, subjects experienced only 267 N (60 lb.) of additional force per elastic cord while in the standing position of the squat exercise (approximately 56 cm of iRED cable extension). The iRED currently has the capability to allow for the connection of up to 6 elastic cords that would provide an additional resistance of approximately 1604 N (360 lb) when the elastic cords are fully stretched. During parabolic flight, a resistive exercise-trained crewmember in a previous project was able to perform the squat exercise with the maximum load setting on the iRED with four elastic cords in parallel (estimated total load of 2764 N; 620 lb.). However, ISS crewmembers have reported discomfort when using the elastic cords since the majority of the additional resistance is applied during a limited ROM, and therefore their use has been limited on ISS (Mark Guilliams, Astronaut Strength, Conditioning, and Rehabilitation Specialist, personal communication). Crewmembers experience a dramatically increased force at the extended portion of each exercise (i.e. standing at the end of a squat exercise) because the elastic cord is relaxed at the beginning of the exercise (no resistance) and does not become stretched until about midway through the ROM.

It is unclear at this time why the reduced PkF during 0-g could not be explained by a subtraction of static force of body mass from PkF in 1-g. It is likely that this difference could be explained by an effect of inertia. Similarly, we cannot explain changes in PkF in the other axes during 0-g compared to 1-g. It would be tempting to infer that the effect of exercise in 0-g may have caused these differences in the x- and y-axes, but video motion capture and kinematic analysis would be required to confirm these suppositions.

Application of iRED Training as a Countermeasure

Previous bed rest studies that have shown that resistive training is an effective countermeasure to loss of muscle mass and bone mineral density have employed maximal or near maximal efforts during either DCER (3,4,17), isokinetic (9), or isometric exercise (1). Elastomer-based training has been shown to be effective in rehabilitative settings or exercise training of the elderly (16), but no studies have been performed to date that examined the effectiveness of elastomer-based resistive exercise as a countermeasure during bed rest or space flight. A recent 16-week training study from our laboratory (15) suggested that iRED training in ambulatory subjects may increase muscle strength and mass, but may not be as effective as traditional free weight exercises. Similarly, preliminary analysis of bone mineral density data from this same training study suggested that free weight training resulted in a significant increase in lumbar bone mineral density while iRED training had no effect.

Two potential issues with elastomer-based training are that it provides an ascending force curve during exercise and that the force during the eccentric phase is less than during the concentric phase. Elastomer-based training may not provide an adequate training stimulus throughout the range of motion in some exercises because the resistance is too low at the lower portion of the ROM and/or crewmembers may not be able to complete the exercise through the entire ROM because the resistance is too great when the iRED cable is extended at the top of the ROM. In addition, we have observed that due to the elastomer-based resistance of the iRED the force that the subjects experience during the eccentric portion of the squat exercise is 60 to 80% of that experienced during the concentric portion of the exercise (Figure 5). Some authors (5,6,7,20) have suggested that a lower eccentric load may reduce the effectiveness of a countermeasure program. However, no studies have been performed to date to determine the effective levels of eccentric exercise required for the maintenance of muscle mass and bone mineral density during space flight or bed rest.

INSERT Figure 5

Conclusions

The foot-ground reaction force in the resultant and the TW while exercising with the iRED in 0-g was reduced compared to 1-g exercise when the absolute load setting of the iRED was maintained between conditions. Previous experience during bed rest (1, 3,4,9,17,19) suggests that high intensity resistive exercise may be required to maintain muscle strength and bone mass. Although the iRED may not be capable of delivering resistances equal to the exercise intensity employed in these ground-based studies, there is currently no data available to determine the minimum intensity, volume, and frequency of resistance exercise necessary during space flight. However, the efficacy of a resistive exercise countermeasure during space flight may be enhanced as more advanced devices become available that are able to produce higher resistances, greater eccentric forces, and high forces across the entire ROM.

Acknowledgements

The investigators would like to thank the subjects for their participation in this project; Mike Rapley from the NASA-JSC Exercise Physiology Laboratory with flight logistics and organization; the NASA-JSC Anthropometrics and Biomechanics Laboratory for assistance with data collection and analysis; Noel Skinner and the NASA-JSC Test Subject Facility for assistance with test subject certification; and the NASA-JSC Reduced Gravity Office for assistance preparing for and during flight.

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Table 1. Peak force measured during normal (1-g) and microgravity (0-g) exercise. The positive z-axis represented the direction from the head to the feet of the subject, the positive x-axis was directed from the subject forward, and the positive y-axis was oriented from the subject to his left.

		Peak Force (N)		
Exercise	Condition	X-axis	Y-axis	Z-axis
Squat	1-g	-66.9±50.7	-69.1±27.0	1670.5±301.8
	0-g	-117.2±30.2	-84.2±12.6	683.6±33.0*
Deadlift	1-g	-68.0±14.3	-133.0±15.8	1721.7±69.4
	0-g	6.7±21.4*	-101.9±16.3	729.2±26.2*
Heel Raise	1-g	-37.6±25.0	-70.9±9.6	1664.4±66.5
	0-g	-32.4±11.7	-29.4±12.6*	752.2±29.0*

*Significantly different from 1-g

Table 2. Mean range of motion (ROM) and time to complete one repetition during normal (1-g) and microgravity (0-g) exercise

Exercise	Condition	ROM (cm)	Time (sec)
Squat	1-g	47.3±1.0	2.0±0.1
	0-g	46.5±2.5	2.1±0.1
Deadlift	1-g	45.0±1.1	1.6±0.0
	0-g	43.8±0.8	1.6±0.0
Heel Raise	1-g	10.2±0.6	2.5±0.1
	0-g	10.1±0.7	2.4±0.1

Figure Captions

Figure 1. The interim Resistance Exercise Device that has been deployed for use on the International Space Station as a countermeasure to musculoskeletal deconditioning.

Figure 2. Mean peak force per repetition across all sets in the resultant vector during normal (1-g) and microgravity (0-g) exercise

Figure 3. Mean total work per repetition across all sets in the resultant vector during normal (1-g) and microgravity (0-g) exercise

Figure 4. Mean peak force in z-axis across all sets in normal gravity exercise minus the static force of body mass (1-g w/o BM) and during microgravity exercise (0-g)

Figure 5. The relationship between the distances that the iRED cable is pulled to the force received by the subject during a representative squat exercise performed as part of an ambulatory training study (15). The force is least at the bottom of the range of motion and greatest at the top of the range of motion (standing).

Figure 1

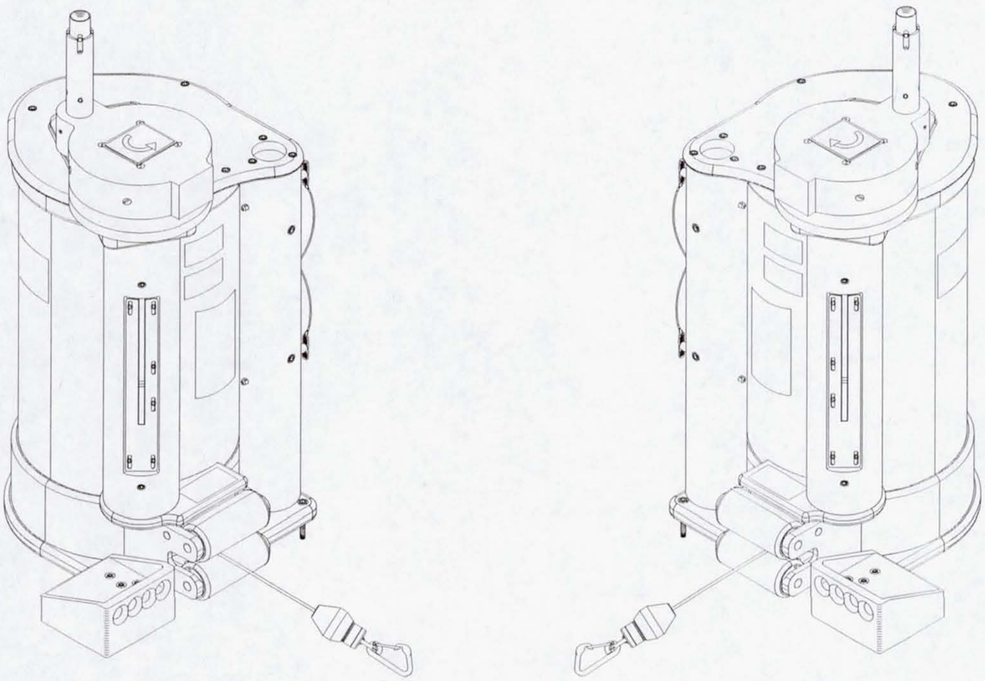

Figure 2

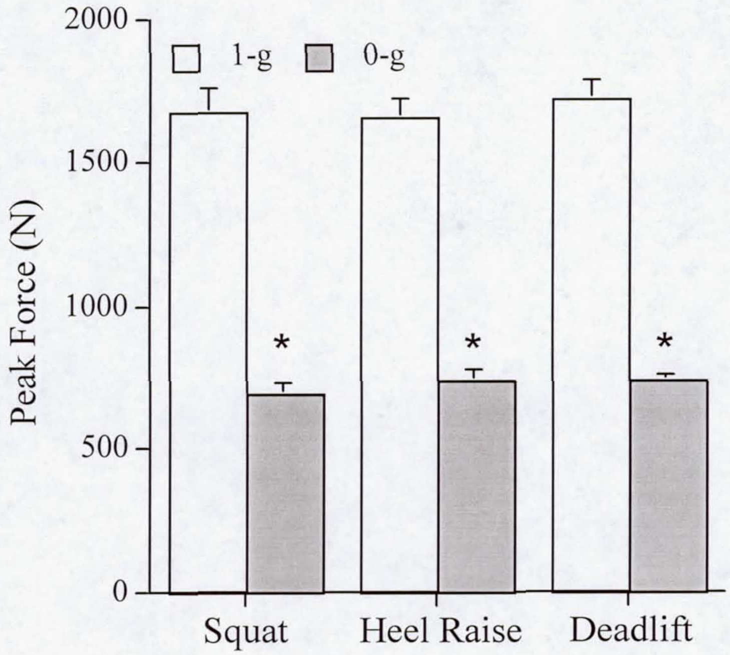
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Figure 3

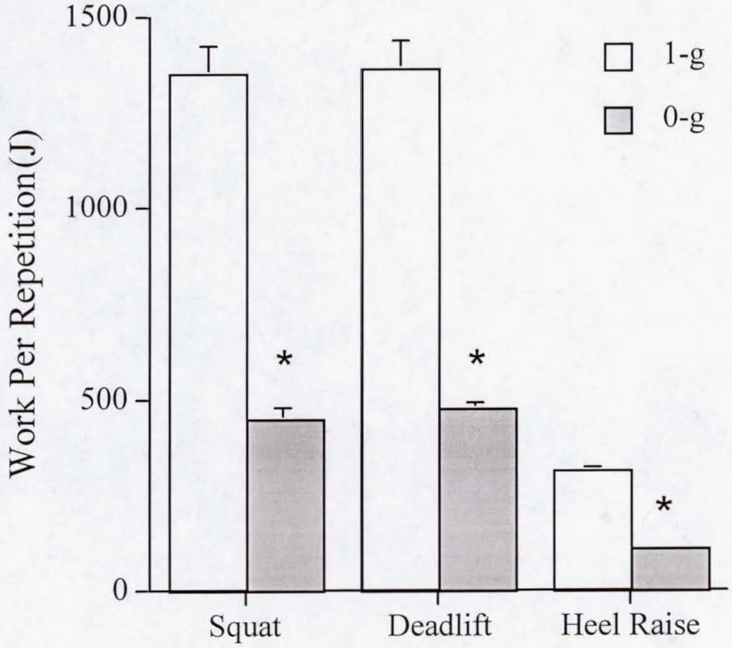
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Figure 4

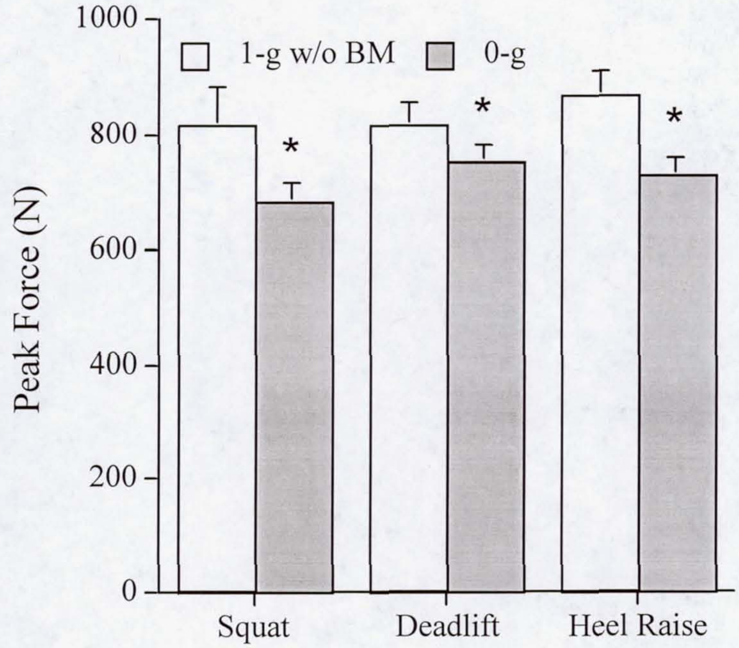
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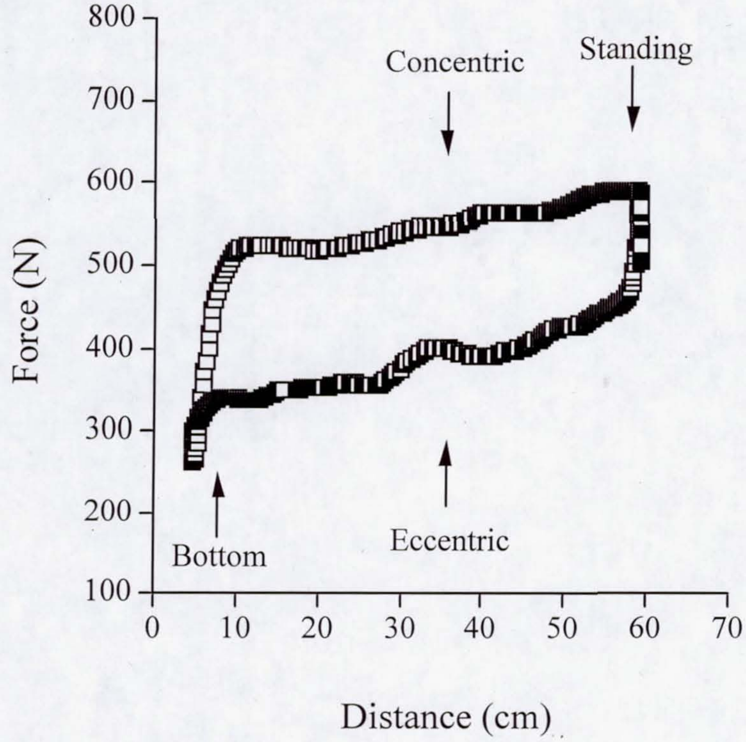
Figure 5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