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## **Summary**

This study compares squat and deadlift exercises performed with two different loading configurations: (1) on a novel single-cable resistance exercise countermeasure device (ECD) for spaceflight and (2) with free weights. The results compare joint kinematics and kinetics between different loading configurations for each exercise, and also between the two exercises for each loading configuration.

Single-cable versions of the squat (using a harness) and deadlift (using a T-bar) performed on the Hybrid Ultimate Lifting Kit (HULK) ECD have significantly different sagittal plane joint angle kinematics (both peak angle and range of motion (ROM)) as well as joint kinetics (both peak joint moment and joint impulse) versus their free-weight equivalents at the same load. Differences also exist in hip abduction and rotation. Overall, the single-cable configurations tend to reduce peak joint angles, ROMs, peak joint moment, and joint impulse versus free weights. A notable exception is the lumbar joint, which is more heavily loaded for single-cable squats versus free-weight squats. This may have implications for both training benefit and possible risk of injury.

Deadlift and squat exercises work the lower body musculature in different ways, with the deadlift emphasizing hip and lumbar extension and the squat emphasizing knee extension. Based on these findings, we would advocate the use of both movements in the exercise prescriptions of astronaut crews on deep-space missions.

## **Introduction**

During manned NASA missions beyond low Earth orbit, astronauts will encounter microgravity for extended periods. The deleterious effects of extended microgravity on musculoskeletal and cardiovascular health, function, and performance are well documented (Refs. 1 to 3). Exercise countermeasure devices (ECDs) are used to maintain musculoskeletal and cardiovascular health and performance during spaceflight (Ref. 4).

### **Exercise Countermeasure Devices**

The purpose of an ECD designed for resistance training is to provide an anatomically localized loading stimulus to mitigate musculoskeletal deconditioning in microgravity. The mechanisms that supply the resistance of spaceflight ECDs cannot rely on gravity. Various methods exist to interface the device and the exerciser. These different loading configurations can impact exercise performance, but not all candidate ECDs can be prototyped, manufactured, and tested during the design process (Ref. 5). Latest generation exercise devices are being designed with the assumption that limited vehicle volume will restrict device size, hence single-cable approaches are under more consideration than dual-cable approaches. Computational biomechanical modeling provides answers to specific questions that aid the ECD design process, such as these: What are the biomechanical differences between exercises performed on an ECD and ground-based free-weight exercise? Does the loading configuration (e.g., barbell versus harness) affect the resulting localized loading?

### **Squat and Deadlift Exercises in Space**

The lumbar spine, hip, and knee joints are sites where high localized loss of both bone and muscle occur in astronauts (Refs. 6 and 7). Resistance exercise prescriptions for astronauts generally target these sites.

The squat is a classic lower body exercise, working the lower limb musculature, hips, and core (Ref. 8). The deadlift also enhances hip, thigh, and back strength, with additional involvement of the shoulders and forearms (Ref. 9).

The squat and deadlift are inherently different exercises. The squat is simultaneous in its execution among the major joints of interest, whereas the deadlift is more sequential in nature. Also, the two exercises have different sticking points and exhibit different trunk positions (Ref. 10). Therefore, they could produce different training adaptations as exercise countermeasures for spaceflight. Ideally, any candidate ECD would support performing both exercises.

Current prototype ECDs provide a single-cable or dual-cable attachment to a bar or harness. Single-cable devices (Figure 1) may be beneficial for spaceflight because they have a smaller volume than dual-cable devices. Commercially, exercise devices with single-cable and harness interfaces have produced increased muscular hypertrophy (in conjunction with eccentric overloading applied via a flywheel) (Ref. 11).

Differences in kinematics and kinetics between single-cable exercises performed on ECDs versus free weights are currently unknown. The purposes of this study were to compare the kinematics and kinetics during squat and deadlift exercises performed with single-cable loading versus free weights, and squat versus deadlift exercises when performed with both loading configurations. Our first two hypotheses were that there would be differences in joint angles and joint torques between squats and deadlifts, respectively, performed using free weights versus a single-cable configuration. The third hypothesis was that there would be differences between the single-cable versions of the squat and deadlift exercises themselves.

## Methods

### Hybrid Ultimate Lifting Kit Exercise Countermeasure Device

The Hybrid Ultimate Lifting Kit (HULK) is a prototype ECD developed by ZIN Technologies. HULK provides resistance through a hybrid mechanism using both gas cylinders and electric motors through a set of pulleys (Refs. 12 and 13).

HULK, shown in Figure 1, measures approximately 122 by 61 by 15 cm. The exerciser either grasps a bar or dons a harness, which is in turn connected by a cable to the resistance apparatus.

### Participant

One person participated in this pilot study. The 46-year-old male was a regular resistance trainee, in excellent health, with a height of 174 cm and a body mass of 68 kg. After becoming familiar with the HULK device, the participant provided informed consent. The NASA Institutional Review Board approved this evaluation.

### Exercise Protocol and Input Variables

The participant performed squats under two conditions: using a barbell free weight and using a single-cabled harness (YoYo Technology AB) on HULK. The participant performed deadlifts under two conditions: using a barbell free weight, and using a T-bar attachment on HULK. The knurled aluminum T-bar measured 51 by 3 cm (diam.) with a mass of 3.9 kg.

The participant performed conventional deadlifts and squats as described in References 9 and 14, regardless of loading configuration. The participant used a dual-pronated grip for all deadlifts.

Prior to data collection, an exercise physiologist evaluated the participant to determine his three-repetition maxima (3 RM). The load for this study was 115 lb (52 kg), an appropriate medium training load corresponding to the participant's estimated 8 to 12 RM.



Figure 1.—Hybrid Ultimate Lifting Kit (HULK) device.  
(a) Configured for single-cable deadlift with T-bar operation. (b) Configured for squat with harness operation.

The participant maintained a fixed, self-selected cadence for deadlifts ( $2.75 \pm 0.12$  sec) and squats ( $2.75 \pm 0.21$  sec) aided by a metronome. Each trial was five repetitions. An experienced athletic coach verified proper form.

## Experimental Setup

Data collection occurred in the Exercise Countermeasures Laboratory (ECL) at NASA's Glenn Research Center.

*Motion history:* A 12-camera motion analysis system (BTS Bioengineering, SMART DX) collected the participant's motion history at 100 Hz. The system tracked the spatial position of spherical reflective markers, 10 mm in diameter, placed at key anatomical sites. The system was calibrated within the participant's activity volume according to the manufacturer's procedures. Calibration error was  $<0.1$  mm. A static pose of the participant was used to scale a biomechanical model to the participant's anthropometrics.

BTS's SMARTtracker<sup>®</sup> and SMARTanalyzer<sup>®</sup> software programs were used to remove spurious marker trajectories, interpolate dropouts, and remove stray reflections using the manufacturer's recommended procedures.

*Ground reaction forces (GRFs):* Two 40- by 60-cm quartz crystal piezoelectric force plates (BTS Bioengineering, P-6000) measured bilateral GRF at 100 Hz. The Smart-DX system synchronized the GRF and motion data automatically.

The participant stood with the insertion point of the cable into the HULK device lying between the feet and the force plates (Figure 1). The participant performed both exercises within a 53- by 34-cm footprint to simulate the anticipated in-flight surface area restrictions of a single-cable device.

*Applied external loads:* Load cells (Omega Inc., Miniature Series, LC-300) and encoders (US Digital, E5 Series) in line with the HULK device cable recorded the time history of the external loads the device produced and the cable displacement, respectively, at a sampling rate of 100 Hz. The exercise device was programmed with an inertial loading profile that mimicked an equivalent free-weight load.

*Data processing:* Motion capture, GRF, and external loads data were filtered in MATLAB<sup>®</sup> (The Mathworks, Inc.) at 6 Hz using an eight-pole Butterworth filter. Filtering of external forces occurred both before importing the data into OpenSim (Stanford University). Kinematic data filtering occurred before inverse dynamics.

## OpenSim Modeling

The OpenSim biomechanical models were scaled versions of the full-body model (Ref. 15). The model contains 22 body segments and 80 lower limb muscles. The modeling efforts followed the workflow recommended in the user documentation (Ref. 16): model scaling, inverse kinematics, and inverse dynamics. Total squared error was  $<0.5$  cm in the static pose during scaling and  $<2.5$  cm for the exercises during inverse kinematics. The maximum single marker error was  $<5$  cm.

Harness loads (magnitude, direction, and point of application) were calculated from the measured cable tension force using an optimizer that minimizes the residual forces on the pelvis in a least-squared-error sense. T-bar loads were applied at the center of the T-bar and directed along the cable.



## Statistical Methods

*Ensemble averaging:* Joint angles and moments were plotted as ensemble averages, time normalized to 101 samples from 0 (repetition start) to 1.0 (repetition completion) in increments of 0.01. At each time-normalized sample, the mean and standard deviation of the five repetitions were computed.

*Statistical significance testing:* Pairwise comparisons of trajectory means at each time-normalized point used Student's t-test between lifts. Two trajectories exhibited significant phase differences if 10 consecutive corresponding samples revealed a significant difference ( $p < 0.01$ ). This method for performing multiple pairwise comparisons was preferred over a Bonferroni adjustment, which would be unnecessarily conservative, because motion trajectory samples are highly correlated.

*Kinematics:* Peak angle and range of motion (ROM) of each joint were compared using Student's t-test ( $p < 0.01$ ). Where significant differences occurred, the effect size was calculated using Cohen's  $d$  (Ref. 17). A "substantial" effect constituted a  $d$ -value of 1.0 or greater (Ref. 18). Peak angle is the maximum angle in the direction of motion during each repetition. ROM is the maximum angle minus the minimum angle with their variances added.

*Kinetics:* Peak joint moment and angular impulse were also compared using the same statistical methods used for the kinematics. Peak moment is the maximum moment value achieved in the direction of motion during each repetition. Angular impulse is the time integral of the moment curve for each repetition.

*Percent change:* Percent changes reported in this article are based on the magnitude of the compared quantities in question, regardless of sign (e.g., a change from a negative value to a less negative value represents a decrease). For compared quantities with opposite signs, the percent change will have the same sign as the new value, not the "compared to" value.

## Results

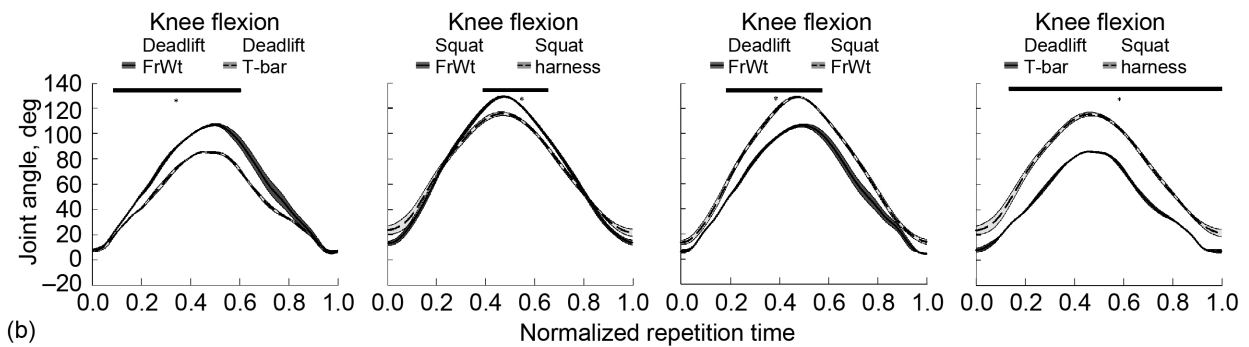
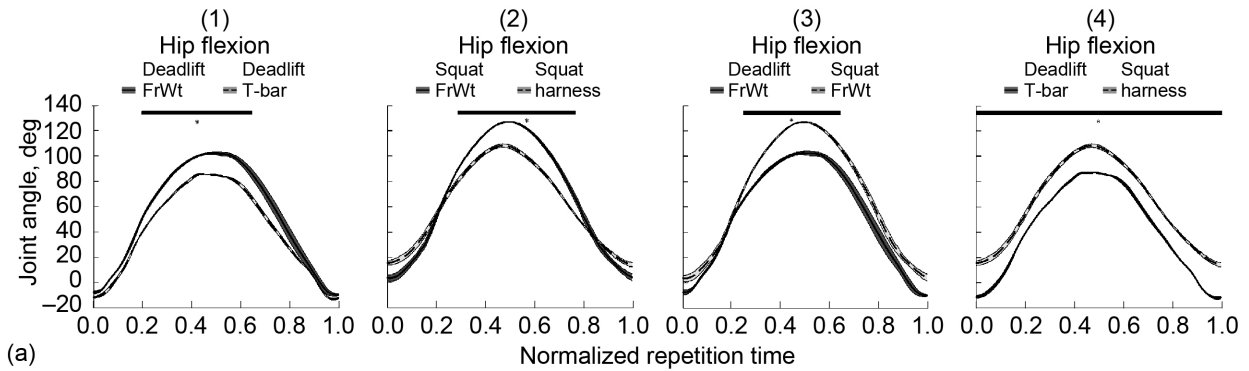
For all joint articulations, a positive value indicates motion in the direction specified. A negative value indicates motion in the opposite direction (e.g., knee flexion is positive and knee extension is negative).

### Joint Kinematics

Figure 2 to Figure 4 compare the kinematic trajectories for all four exercise/loading configuration combinations. Figure 2 compares hip flexion (a) and knee flexion (b), respectively. Figure 3 compares hip abduction (a) and hip external rotation (b), respectively. Figure 4 compares lumbar extension (a) and ankle dorsiflexion (b), respectively. Phases with significant differences ( $p < 0.01$ ) are denoted with solid bars and asterisks.

Figure 5 and Figure 6 compare peak joint angles and ROMs, respectively, for all four loading conditions. The tables below each figure report percentage changes and effect size ( $d$ ) and identify significant differences ( $p < 0.01$ ).

Single-cable exercises produced generally lower peak angles and ROMs than their free-weight counterparts in the sagittal plane, with more mixed results in the other planes. Squats produced higher peak joint angles and ROMs in the sagittal plane than deadlifts, except for the lumbar joint, where the reverse was true.



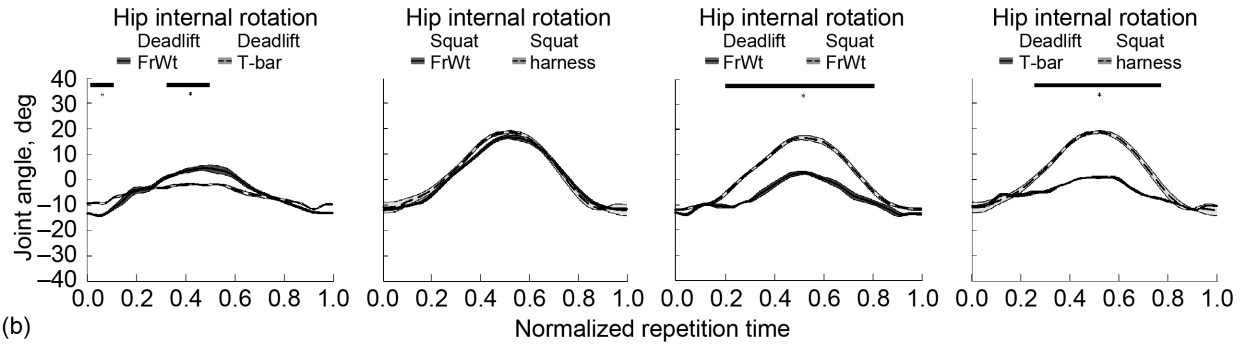
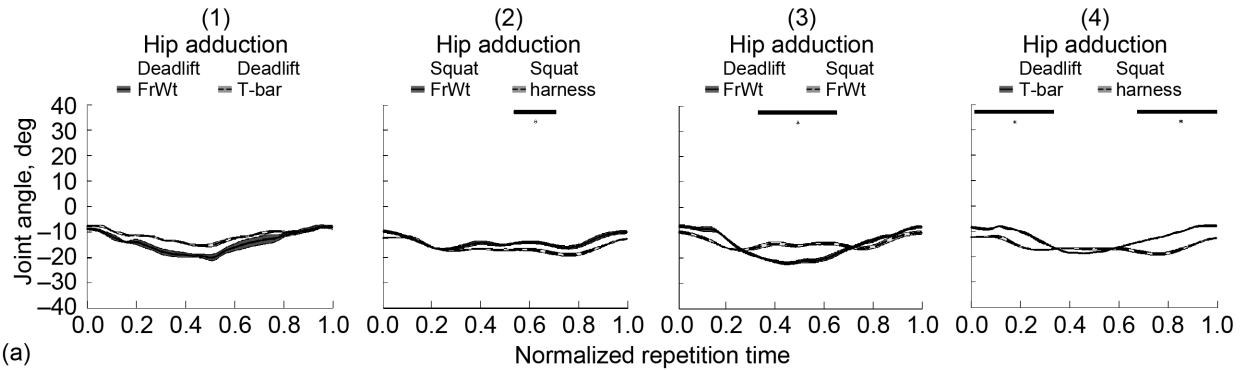
(c)

Joint angle	Hip flexion, deg				Knee flexion, deg			
	Deadlift		Squat		Deadlift		Squat	
Free weight	Peak	ROM	Peak	ROM	Peak	ROM	Peak	ROM
	102.6±1.3	112.7±1.6	127.0±0.2 †	123.5±2.6 ‡	106.4±1.3	102.0±1.3	129.2±0.7 †	115.9±1.7 ‡
Hybrid Ultimate Lifting Kit (HULK) (Single cable)	Deadlift (T-bar)		Squat (harness)		Deadlift (T-bar)		Squat (harness)	
	Peak	ROM	Peak	ROM	Peak	ROM	Peak	ROM
	86.9±0.2 †	98.9±1.0 †	108.3±1.4 †‡	94.1±2.2 †‡	85.8±0.5 †	78.8±1.4 †	115.6±1.4 †‡	94.0±3.2 †‡

† = Significantly different ( $p < 0.01$ ) than free weight, same exercise.

‡ = Significantly different ( $p < 0.01$ ) than deadlift, same loading type.

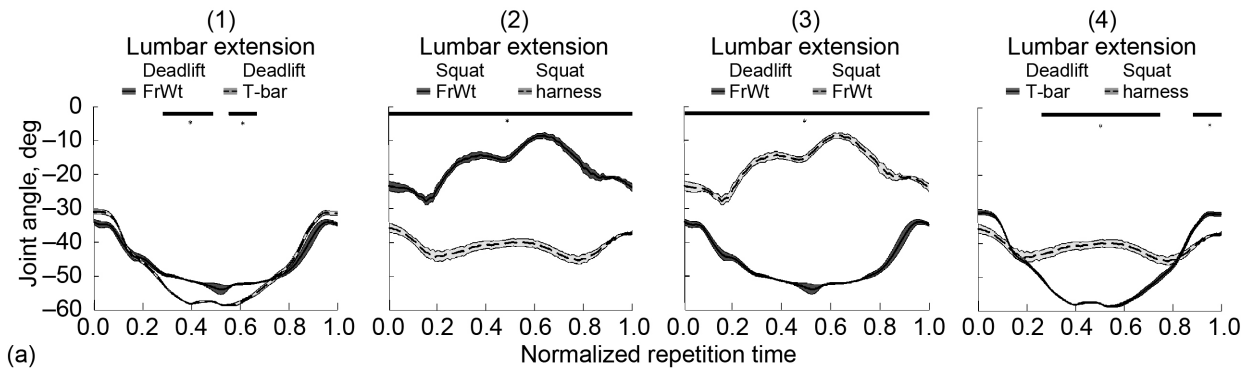
Figure 2.—Ensemble averages for hip flexion (a) and knee flexion (b) joint angles versus normalized repetition time. Pairwise trajectory comparisons are deadlift with free weight (FrWt) versus deadlift with T-bar (1), squat with FrWt versus squat with harness (2), deadlift with FrWt versus squat with FrWt (3), and deadlift with T-bar versus squat with harness (4). Solid black bar labeled with (\*) indicates areas of significant difference ( $p < 0.01$  for 10 or more normalized samples). (c) Table showing peak angle and range of motion (ROM) for each trial (mean±SD).



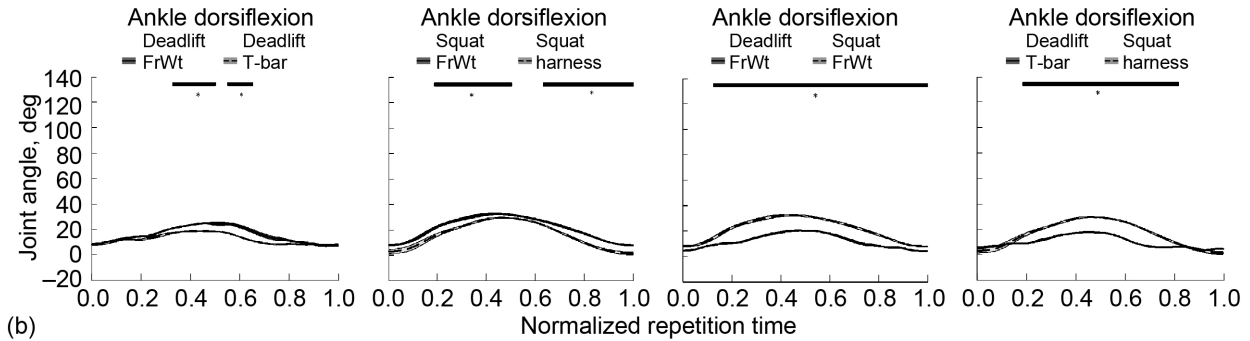
Joint angle	Hip adduction, deg				Hip internal rotation, deg			
	Deadlift		Squat		Deadlift		Squat	
Free weight	Peak	ROM	Peak	ROM	Peak	ROM	Peak	ROM
	-22.0±0.5	14.5±0.7	-16.8±0.5 †	7.0±0.6 †	2.7±0.7	16.7±1.0	16.7±0.8 †	28.7±0.8 †
Hybrid Ultimate Lifting Kit (HULK) (Single cable)	Deadlift (T-bar)		Squat (harness)		Deadlift (T-bar)		Squat (harness)	
	Peak	ROM	Peak	ROM	Peak	ROM	Peak	ROM
	-18.7±0.4 †	10.9±0.4 †	-19.0±0.5 †	6.9±0.7 †	0.9±0.2 †	12.9±0.3 †	18.8±0.5 ††	30.8±2.1 †

† = Significantly different ( $p < 0.01$ ) than free weight, same exercise.  
 †† = Significantly different ( $p < 0.01$ ) than deadlift, same loading type.

Figure 3.—Ensemble averages for hip adduction (a) and hip internal rotation (b) joint angles versus normalized repetition time. Pairwise trajectory comparisons are deadlift with free weight (FrWt) versus deadlift with T-bar (1), squat with FrWt versus squat with harness (2), deadlift with FrWt versus squat with FrWt (3), and deadlift with T-bar versus squat with harness (4). Solid black bar labeled with (\*) indicates areas of significant difference ( $p < 0.01$  for 10 or more normalized samples). (c) Table showing peak angle and range of motion (ROM) for each trial (mean±SD).



(a)



(b)

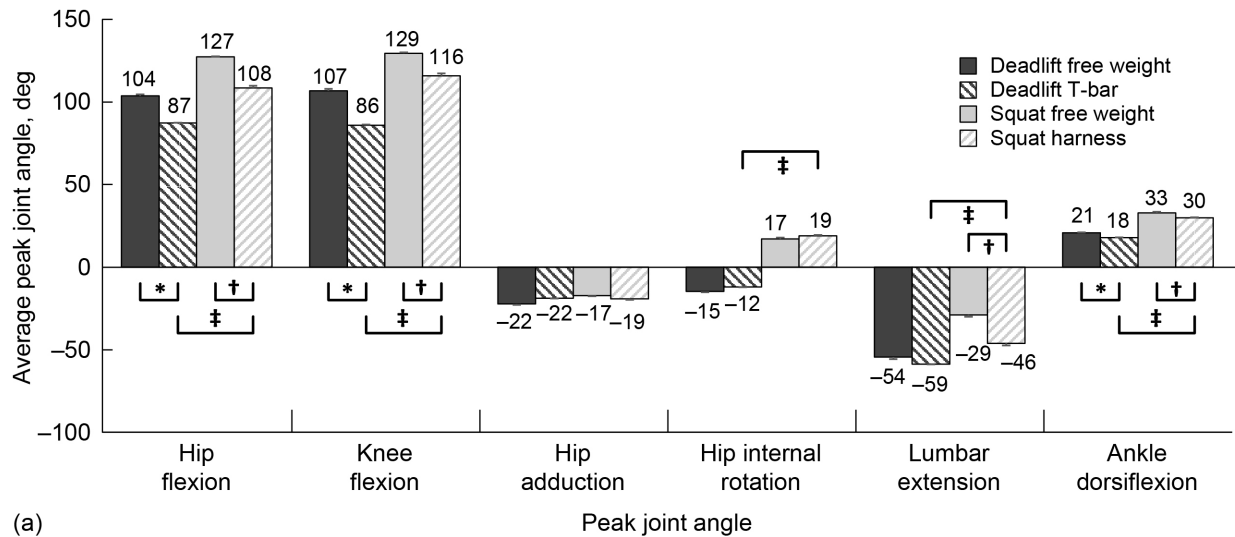
Joint angle	Lumbar extension, deg				Ankle dorsiflexion, deg			
	Deadlift		Squat		Deadlift		Squat	
Free weight	Peak	ROM	Peak	ROM	Peak	ROM	Peak	ROM
	-53.9±0.7	19.9±1.6	-27.8±1.1 †	19.3±1.4	20.5±0.5	16.1±0.6	32.7±0.6 †	24.8±0.7 †
Hybrid Ultimate Lifting Kit (HULK) (Single cable)	Deadlift (T-bar)		Squat (harness)		Deadlift (T-bar)		Squat (harness)	
	Peak	ROM	Peak	ROM	Peak	ROM	Peak	ROM
	-58.5±0.6 †	27.5±0.6 †	-35.8±1.3 ††	9.5±1.7 ††	17.9±0.1 †	14.1±0.4 †	29.7±0.3 ††	28.2±1.1 ††

(c)

† = Significantly different ( $p < 0.01$ ) than free weight, same exercise.

†† = Significantly different ( $p < 0.01$ ) than deadlift, same loading type.

Figure 4.—Ensemble averages for lumbar extension (a) and ankle dorsiflexion (b) joint angles versus normalized repetition time. Pairwise trajectory comparisons are deadlift with free weight (FrWt) versus deadlift with T-bar (1), squat with FrWt versus squat with harness (2), deadlift with FrWt versus squat with FrWt (3), and deadlift with T-bar versus squat with harness (4). Solid black bar labeled with (\*) indicates areas of significant difference ( $p < 0.01$  for 10 or more normalized samples). (c) Table showing peak angle and range of motion (ROM) for each trial (mean±SD).

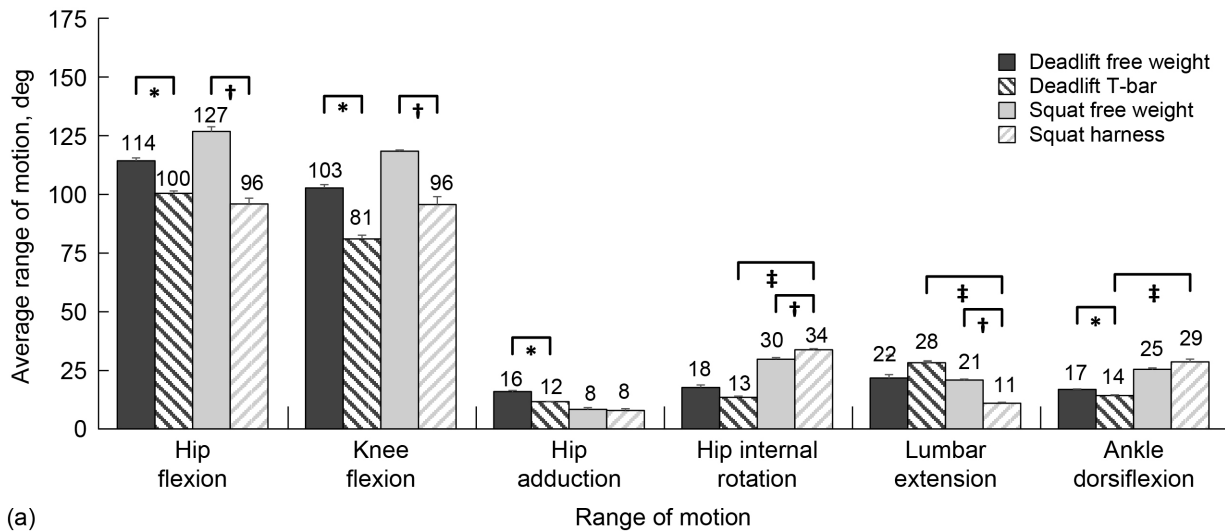


(a)

	Hip flexion		Knee flexion		Hip adduction		Hip internal rotation		Lumbar extension		Ankle dorsiflexion						
	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size					
Deadlift—Free weight versus T-bar	-16	27	*	-20	24	*	-15.0	9.10	-18	7.0	7.9	4.9	-14.0	14.0	*		
Squat—Free weight versus harness	-15	19	†	-11	12	†	12.0	4.40	11	2.9	59.0	15.0	†	-9.1	5.9	†	
Deadlift—T-bar versus squat harness	24	22	‡	35	28	‡	2.1	1.03	-258	78.0	‡	-21.0	14.0	‡	67.0	50.0	‡

(b)

Figure 5.—(a) Comparison of averaged peak joint angle for deadlift with free weight, deadlift on HULK with T-bar, squat with free weight, and squat on HULK with harness. (b) Table listing percent change and effect size (Cohen's *d*) for three comparisons, with significant differences identified for deadlift with free weight versus deadlift T-bar (\*), squat with free weight versus squat with T-bar (†) and deadlift with T-bar versus squat with harness (‡).



(a)

	Hip flexion		Knee flexion		Hip adduction		Hip internal rotation		Lumbar extension		Ankle dorsiflexion							
	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size						
Deadlift—Free weight versus T-bar	-12.0	12.0	*	-21	15.0	*	-27.0	11.00	*	-24	5.0	30	6.1	-16	8.5	*		
Squat—Free weight versus harness	-24.0	14.0	†	-19	9.5	†	-5.1	0.54		13	6.4	†	-47	23.0	†	13	3.4	
Deadlift—T-bar versus squat harness	-4.5	2.4		18	5.6		-32.0	6.60		151	39.0	‡	-61	53.0	‡	101	17.0	‡

(b)

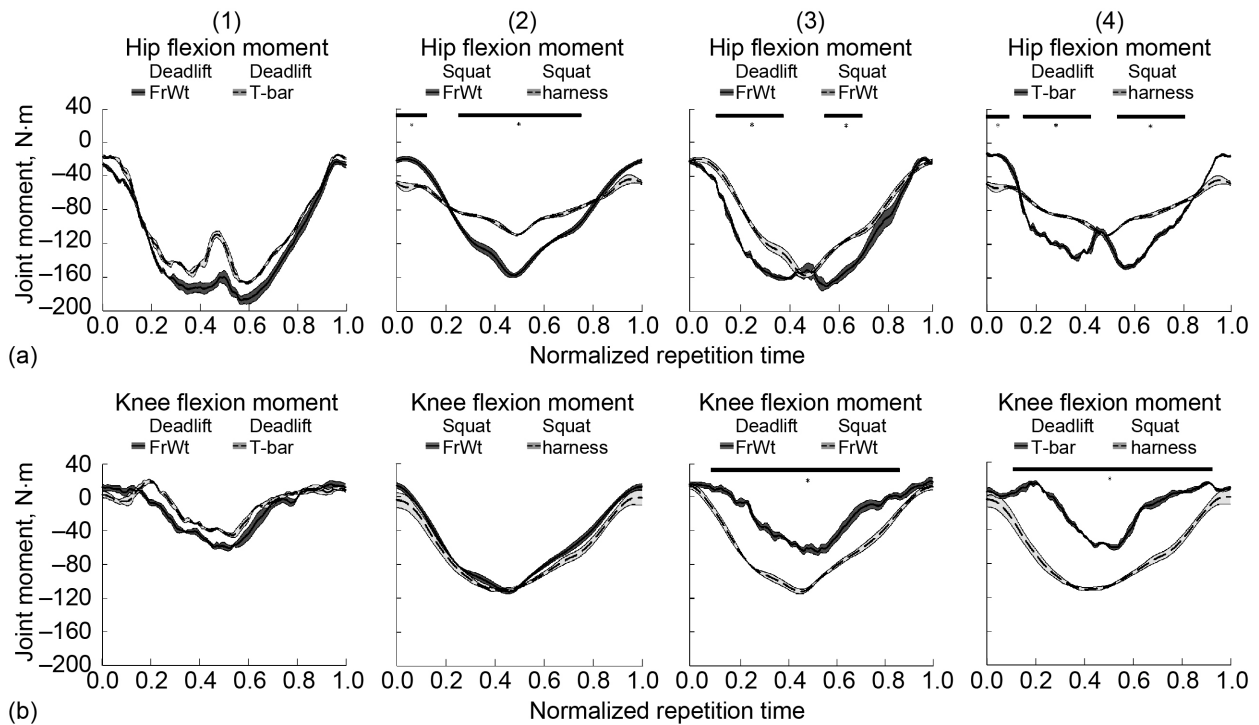
Figure 6.—Comparison of the averaged ranges of motion in degrees for deadlift with free weight, deadlift on Hybrid Ultimate Lifting Kit (HULK) with T-bar, squat with free weight, and squat on HULK with harness. (b) Table listing percent change and effect size (Cohen’s *d*) for three comparisons, with significant differences identified for deadlift with free weight versus deadlift with T-bar (\*), squat with free weight versus squat with T-bar (†), and deadlift with T-bar versus squat with harness (‡).

### Joint Kinetics

Figure 7 to Figure 9 compare the joint moment trajectories for all four exercise/loading configuration combinations. Figure 7 compares hip flexion moment (a) and knee flexion moment (b), respectively. Figure 8 compares hip abduction moment (a) and hip external rotation moment (b), respectively. Figure 9 compares lumbar extension moment (a) and ankle dorsiflexion moment (b), respectively. Phases with significant differences ( $p < 0.01$ ) are denoted with solid bars and asterisks.

Figure 10 and Figure 11 compare peak joint moments and angular impulses, respectively, for all four loading conditions. The tables below each figure report percentage changes and effect size (*d*) and identify significant differences ( $p < 0.01$ ).

Single-cable exercises produced lower peak moments than their free-weight counterparts at the hip and lumbar joints. Deadlifts produced higher joint moments and angular impulses for hip and lumbar extension than squats, while the reverse was true for the knee and ankle joints. Deadlifts produced internal hip rotation, while squats produced external hip rotation.

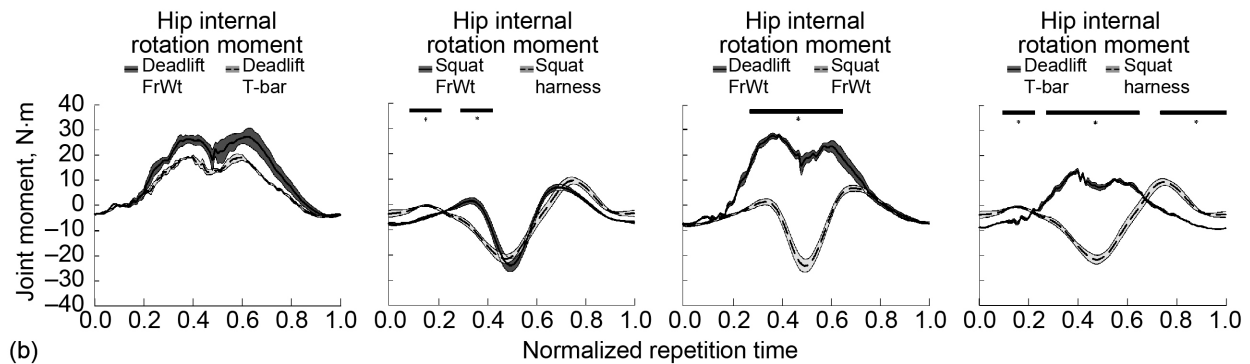
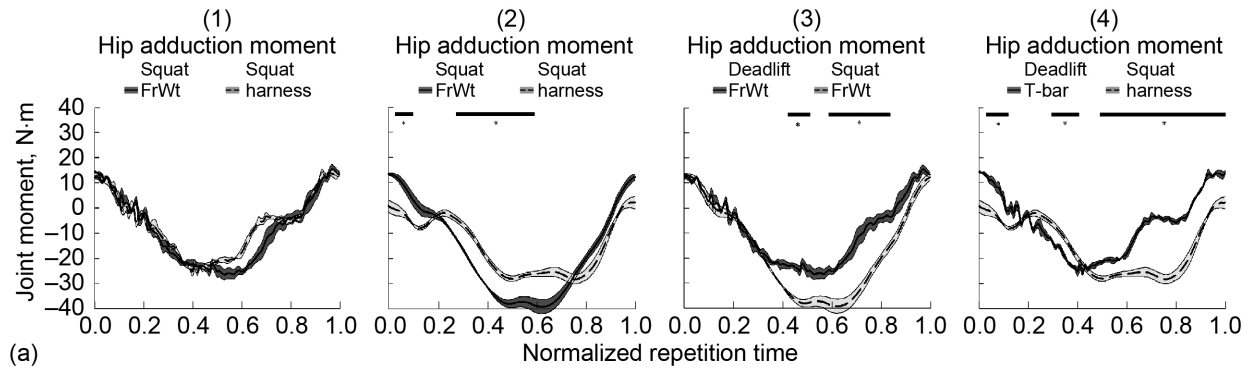


Joint moment	Hip flexion				Knee flexion			
	Deadlift		Squat		Deadlift		Squat	
Free weight	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s
	-169.7±2.3	-85.9±1.7	157.3±2.8 ‡	-86.8±1.3	-65.0±4.8	-15.3±2.3	-112.1±3.1 ‡	-55.9±1.9 ‡
Hybrid Ultimate Lifting Kit (HULK) (Single cable)	Deadlift (T-bar)		Squat (harness)		Deadlift (T-bar)		Squat (harness)	
	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s
	-147.9±1.9 †	-71.9±0.2 †	109.6±4.6 †‡	-76.3±0.9 †‡	-60.9±2.1	-10.0±0.8 †	110.1±8.5 ‡	-64.5±3.5 †‡

† = Significantly different ( $p < 0.01$ ) than free weight, same exercise.

‡ = Significantly different ( $p < 0.01$ ) than deadlift, same loading type.

Figure 7.—Ensemble averages for hip flexion (a) and knee flexion (b) joint moments versus normalized repetition time. Pairwise trajectory comparisons are deadlift with free weight (FrWt) versus deadlift with T-bar (1), squat with FrWt versus squat with harness (2), deadlift with FrWt versus squat with FrWt (3), and deadlift with T-bar versus squat with harness (4). Solid black bar labeled with (\*) indicates areas of significant difference ( $p < 0.01$  for 10 or more normalized samples). (c) Table showing peak moment and impulse for each trial (mean±SD).

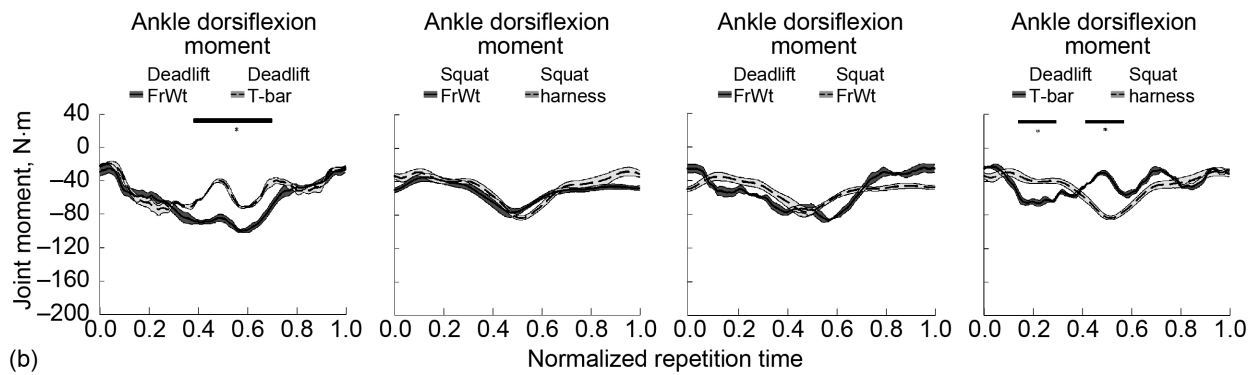
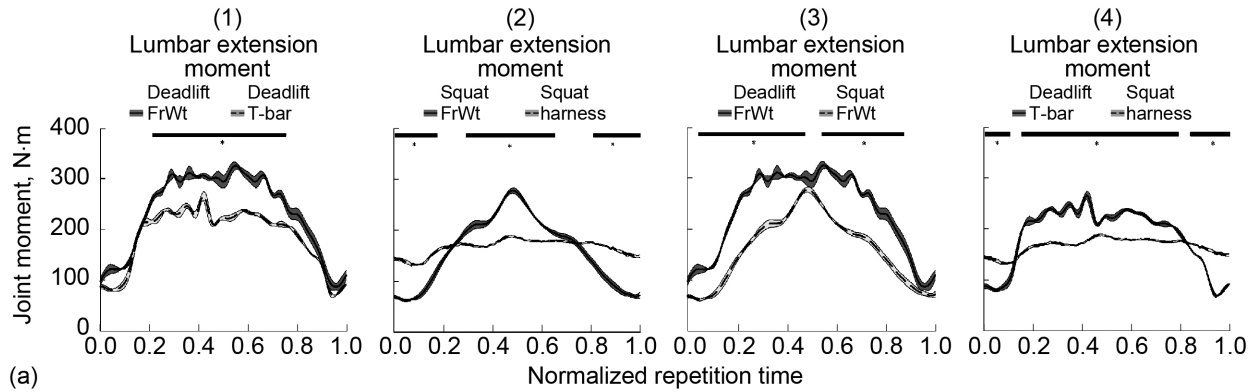


Joint moment	Hip adduction				Hip internal rotation			
	Deadlift		Squat		Deadlift		Squat	
Free weight	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s
	-26.5±1.7	-14.8±0.8	-39.1±0.5 ‡	-16.6±0.6 ‡	27.6±0.7	9.7±1.1	-24.0±1.1 ‡	-3.1±0.6 ‡
Hybrid Ultimate Lifting Kit (HULK) (Single cable)	Deadlift (T-bar)		Squat (harness)		Deadlift (T-bar)		Squat (harness)	
	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s
	-25.9±0.6	-11.3±0.3 †	-28.3±2.5 †	-13.8±0.6 †‡	13.7±1.0 †	5.9±0.3 †	-21.6±1.3 ‡	-8.3±0.3 †‡

† = Significantly different ( $p < 0.01$ ) than free weight, same exercise.  
 ‡ = Significantly different ( $p < 0.01$ ) than deadlift, same loading type.

Figure 8.—Ensemble averages for hip adduction (a) and hip internal rotation (b) joint angles versus normalized repetition time. Pairwise trajectory comparisons are deadlift with free weight (FrWt) versus deadlift with T-bar (1), squat with FrWt versus squat with harness (2), deadlift with FrWt versus squat with FrWt (3), and deadlift with T-bar versus squat with harness (4). Solid black bar labeled with (\*) indicates areas of significant difference ( $p < 0.01$  for 10 or more normalized samples). (c) Table showing peak moment and impulse for each trial (mean±SD).



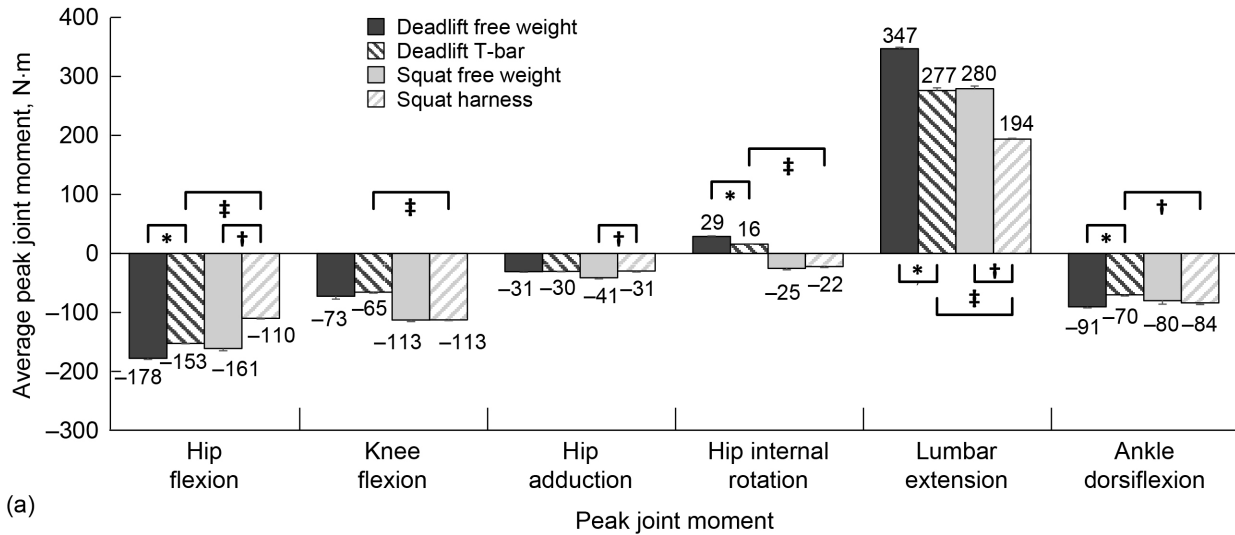


Joint moment	Lumbar extension				Ankle dorsiflexion			
	Deadlift		Squat		Deadlift		Squat	
Free weight	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s
	325.4±6.8	187.1±1.9	277.5±4.8	160.7±2.5 ‡	-86.8±1.1	-42.3±10.6	-77.1±5.0	-51.5±1.8 ‡
Hybrid Ultimate Lifting Kit (HULK) (Single cable)	Deadlift (T-bar)		Squat (harness)		Deadlift (T-bar)		Squat (harness)	
	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s	Peak, N·m	Impulse, N·m/s
	265.3±8.4 †	148.9±1.4 †	190.7±2.4 †	166.0±0.6 †‡	-65.9±1.8 †	-34.3±8.7 †‡	-83.7±5.2 ‡	-46.8±2.5 ‡

† = Significantly different ( $p < 0.01$ ) than free weight, same exercise.

‡ = Significantly different ( $p < 0.01$ ) than deadlift, same loading type.

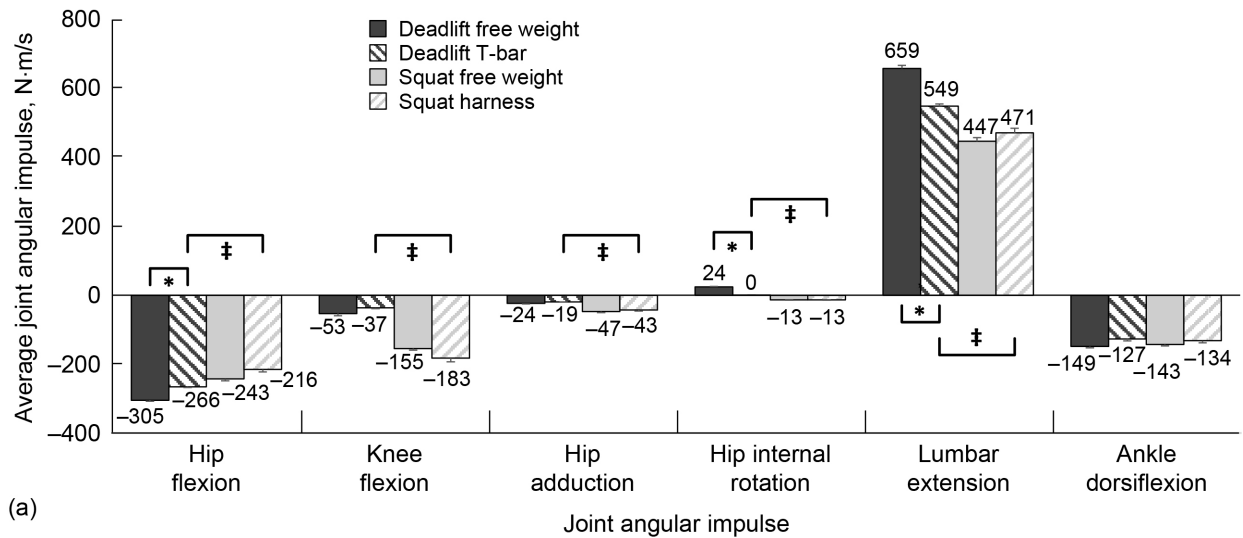
Figure 9.—Ensemble averages for lumbar extension (a) and ankle dorsiflexion (b) joint angles versus normalized repetition time. Pairwise trajectory comparisons are deadlift with free weight (FrWt) versus deadlift with T-bar (1), squat with FrWt versus squat with harness (2), deadlift with FrWt versus squat with FrWt (3), and deadlift with T-bar versus squat with harness (4). Solid black bar labeled with (\*) indicates areas of significant difference ( $p < 0.01$  for 10 or more normalized samples). (c) Table showing peak moment and impulse for each trial (mean±SD).



	Hip flexion		Knee flexion		Hip adduction		Hip internal rotation		Lumbar extension		Ankle dorsiflexion						
	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size					
Deadlift—Free weight versus T-bar	-14	20	*	-9.80	1.90	-0.7	0.20	-45	16.0	*	-20	20	*	-23.0	11.00	*	
Squat—Free weight versus harness	-32	18	†	-0.38	0.21	-28.0	7.10	†	-12	1.4	-31	25	†	4.9	0.85		
Deadlift—T-bar versus squat harness	-28	50	‡	72.00	27.00	‡	-1.9	0.50	-240	29.0	‡	-30	25	‡	20.0	6.00	‡

(b)

Figure 10.—(a) Comparison of the averaged peak joint moments in N·m for deadlift with free weight, deadlift on Hybrid Ultimate Lifting Kit (HULK) with T-bar, squat with free weight, and squat on HULK with harness. (b) Table listing percent change and effect size (Cohen's *d*) for three comparisons, with significant differences identified for deadlift with free weight versus deadlift with T-bar (\*), squat with free weight versus squat with T-bar (†), and deadlift with T-bar versus squat with harness (‡).



(b)

	Hip flexion		Knee flexion		Hip adduction		Hip internal rotation		Lumbar extension		Ankle dorsiflexion	
	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size	Percent change	Effect size
Deadlift—Free weight versus T-bar	-13	13.0 *	-31	3.5	-21	4.3	-98.00	21.00 *	-17.0	14.0 *	-15.0	4.70
Squat—Free weight versus harness	-11	4.3	18	3.3	-9	1.4	-0.48	0.05	5.4	2.0	-7.6	2.10
Deadlift—T-bar versus squat harness	-19	9.0 ‡	397	18.0 ‡	125	11.0 ‡	-3,070.00	15.00 ‡	-14.0	7.1 ‡	4.4	0.97

Figure 11.—(a) Comparison of averaged joint angular impulses in N·m/s for deadlift with free weight, deadlift on Hybrid Ultimate Lifting Kit (HULK) with T-bar, squat with free weight, and squat on HULK with harness. (b) Table listing percent change and effect size (Cohen's *d*) for three comparisons, with significant differences identified for deadlift with free weight versus deadlift with T-bar (\*), squat with free weight versus squat with T-bar (†), and deadlift with T-bar versus squat with harness (‡).

## Discussion

This study investigated kinematic and kinetic differences between loading configurations for resistance exercise at the same load. Kinematics and kinetics were compared during squat and deadlift exercises performed with single-cable loading versus free weights, and squat versus deadlift exercises when performed with both loading configurations. We hypothesized that there would be differences in all cases.

### Deadlift: Free Weight Versus Hybrid Ultimate Lifting Kit T-Bar

Peak flexion angles, ROMs, peak joint moments, and joint angular impulses decreased for the sagittal hip, knee, and ankle joints for single-cable (T-bar) deadlifts versus free weights. However, the decrease in peak knee joint moment was not significant, nor were the decreased angular impulses at the knee and ankle. Lumbar joint kinematic differences were not significant, but peak lumbar joint moment and angular impulse decreased when using the T-bar. All noted differences were both statistically significant and substantial based on effect size ( $p < 0.01$ ,  $d > 1.0$ ). This participant adopted a more upright posture when using the T-bar than with free weights (Figure 12).



Figure 12.—Comparison of subject posture during deadlift. (a) At bottom of movement for free weight. (b) At bottom of movement for T-bar on Hybrid Ultimate Lifting Kit (HULK). (c) At top of movement for free weight. (d) At top of movement for T-bar on HULK.

Differences in sagittal plane moments arise from the hand position relative to the feet and the deeper sagittal plane flexion angles with the free weights. This resulted in the free weights eliciting a greater loading stimulus during the deadlift for all lower body sagittal plane joints compared with the T-bar for this participant. For the lumbar joint, the reverse appears to be true. Outside of the sagittal plane, the differences in hip abduction and hip rotation were not significant. Whether these findings are unique to this participant or whether the participant can be trained (e.g., changing posture) to elicit greater training benefit when exercising with a single cable warrants further study.

### **Squat: Free Weight Versus Hybrid Ultimate Lifting Kit Harness**

The peak angle and ROM associated with hip flexion, knee flexion, and lumbar extension decreased when squatting with the single-cable harness versus free weights. The peak angle associated with ankle dorsiflexion decreased when squatting with the harness versus free weights, but there was no significant difference in the ROM. The peak joint moment associated with hip flexion and lumbar extension also decreased for the single-cable exercise, but there was no significant difference in any of the joint angular impulses. Interestingly, the knee and lumbar joints showed no change and decreased extension moments, respectively, but increased joint angular impulse, although not significantly, with the harness versus free weights. This suggests that harness squats placed a higher overall demand on the knee extensors and spinal erectors throughout the movement than free-weight squats did. Hip abduction moment decreased and hip external rotation moment increased with the harness versus free weights, suggesting a potentially greater training benefit outside of the sagittal plane for harness squats. This subject adopted a less upright stance during harness squats, with the head more forward of the pelvis at both the top and the bottom of the movement (Figure 13). Differences in sagittal plane moments arise from a more forward posture and shallower depth for harness squats versus free weights.

### **Hybrid Ultimate Lifting Kit Single Cable: Deadlift Versus Squat**

The T-bar deadlift showed increased peak hip extension moment, lumbar extension moment, and ankle plantar flexion moment, but decreased peak knee extension moment, versus the harness squat.

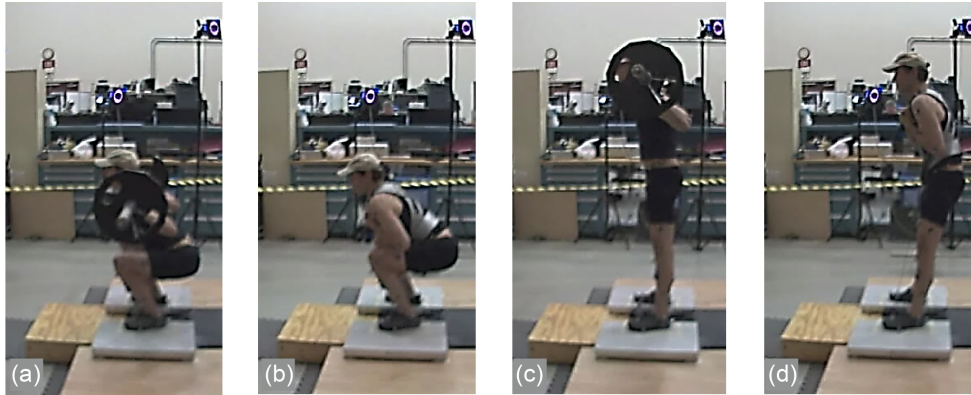


Figure 13.—Comparison of subject posture during squat. (a) At bottom of movement for free weight. (b) At bottom of movement for harness on Hybrid Ultimate Lifting Kit (HULK). (c) At top of movement for free weight. (d) At top of movement for T-bar on HULK.

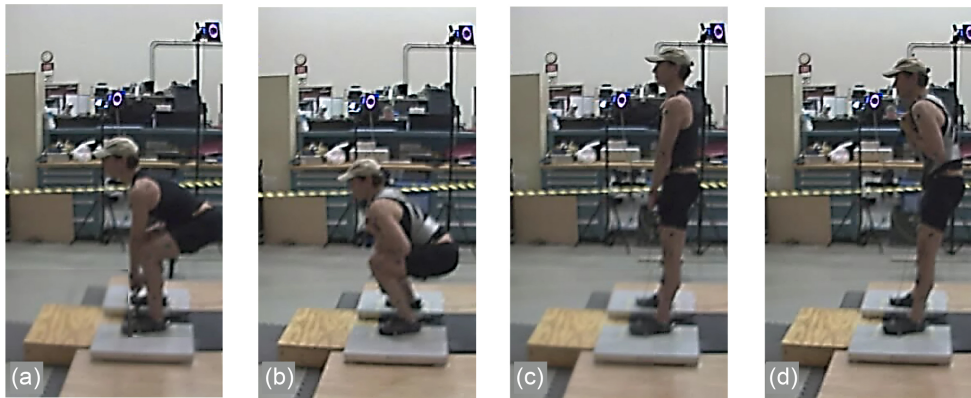


Figure 14.—Comparison of subject posture on Hybrid Ultimate Lifting Kit device. (a) At bottom of movement for T-bar deadlift. (b) At bottom of movement for harness squat. (c) At top of movement for T-bar deadlift. (d) At top of movement for harness squat.

Figure 14 shows that at the bottom of the movement, the participant’s overall body posture is more forward when squatting versus deadlifting relative to the feet. Also note the consistently deeper flexion angles for squats in Figure 2 to Figure 4. At the top of the movement, the participant is noticeably more forward when squatting. This serves to produce a consistently higher load throughout the movement due to the harness. This difference was not observed with the free weights because the participant was able to keep the bar over the heel fore-aft position at both the top and bottom of the movement. This increase in lumbar torque for the harness squat might be a training benefit, but it could also have negative implications both for training (e.g., it limits the weight the participant can squat) or risk of injury to the back. This finding warrants further investigation.

### Significance

To our knowledge, this is the first study to compare biomechanical outcomes between a constant-tension-loaded, single-cable device and free weights for the squat exercise. There have been two studies of squats on a commercial single-cable exercise (Refs. 19 and 20); however, the device was a flywheel device, not constant-tension, and the studies were focused on training adaptation rather than

biomechanics. These studies showed that recumbent squats performed using a single-cable flywheel exercise device produced similar, if not greater, quadriceps muscle use than the back-squat free-weight exercise. The authors therefore concluded that a single-cable flywheel device could serve as a feasible and highly effective in-flight countermeasure.

To our knowledge, this is also the first study to compare the single-cable deadlift's kinematics and kinetics to those of its free-weight counterpart.

The finding that both types of deadlifts emphasize lumbar and hip extension moments (while de-emphasizing knee extension moment) relative to squats at the same system load is consistent with other studies (Refs. 14 and 9).

### **Limitations and Future Work**

The current study is limited by the use of a single participant, but it informs further analyses of the efficacy of proposed ECDs for spaceflight. In particular, these results can inform the selection of exercise prescriptions (choice of exercise, intensity, and volume) and supply valuable inputs for bone and muscle adaptation models that can estimate crew performance after a period of time in space using specific ECDs and exercise prescriptions.

This study reports joint kinematic and joint torque information, but it does not consider muscle and joint forces, muscle activation, and co-activation effects. We plan to report these outcomes, validated by electromyography results, in future publications.

This study does not consider exercise in a microgravity environment, which could produce different kinematics than on Earth. We plan to simulate the effects of microgravity using predictive kinematic modeling in future work.

### **Conclusions**

This study showed that single-cable versions of the squat (using a harness) and deadlift (using a T-bar) performed on the Hybrid Ultimate Lifting Kit (HULK) have different sagittal plane kinematics (peak angle and range of motion) as well as kinetics (peak joint moment and joint impulse) versus their free-weight equivalents at the same load. Kinetic differences also exist in the non-sagittal plane hip articulations (hip abduction and rotation) for the squat exercise, where the free weight produces higher moments. Whether this is dictated by the device or by the subject's choice of posture and kinematics remains unclear.

The results of this study also show that the deadlift and squat exercises work the lower body musculature in different ways. Many of these differences parallel each other, regardless of whether performed with free weights or with single-cable loading configurations on the HULK device. The notable exception is the lumbar joint, which is more heavily loaded for single-cable squats versus free weights. This latter effect has implications for both training and possible risk of injury.

Because of the kinematic and kinetic differences found for the single-cable versions of deadlift and squat, the two exercises should be considered independent and complementary. The external loading method significantly influences acute kinematics and kinetics, and, most likely, training adaptations.

### **References**

1. Grimm, Daniela, et al.: The Impact of Microgravity on Bone in Humans. *Bone*, vol. 87, 2016, pp. 44–56.
2. West, John B.: Physiology of a Microgravity Environment Historical Perspectives: Physiology in Microgravity. *J. Appl. Physiol.*, vol. 89, 2000, pp. 379–384.

3. Trappe, Scott, et al.: Exercise in Space: Human Skeletal Muscle After 6 Months Aboard the International Space Station. *J. Appl. Physiol.*, vol. 106, 2009, pp. 1159–1168.
4. Smith, Scott M., et al.: Benefits for Bone From Resistance Exercise and Nutrition in Long-Duration Spaceflight: Evidence From Biochemistry and Densitometry. *J. Bone Miner. Res.*, vol. 27, no. 9, 2012, pp. 1896–1906.
5. Nicogossian, Arnauld E., et al.: Development of Countermeasures for Medical Problems Encountered in Space Flight. *Adv. Space Res.*, vol. 12, no. 1, 1992, pp. 329–337.
6. Lang, Thomas, et al.: Cortical and Trabecular Bone Mineral Loss From the Spine and Hip in Long-Duration Spaceflight. *J. Bone Miner. Res.*, vol. 19, no. 6, 2004, pp. 1006–1012.
7. Iwamoto, Jun; Takeda, Tsuyoshi; and Sato, Yoshihiro: Interventions to Prevent Bone Loss in Astronauts During Space Flight. *Keio J. Med.*, vol. 54, no. 2, 2005, pp. 55–59.
8. Escamilla, Rafael F.: Knee Biomechanics of the Dynamic Squat Exercise. *Med. Sci. Sports Exerc.*, vol. 33, no. 1, 2001, pp. 127–141.
9. Escamilla, Rafael F., et al.: A Three-Dimensional Biomechanical Analysis of Sumo and Conventional Style Deadlifts. *Med. Sci. Sports Exerc.*, vol. 32, no. 7, 2000, pp. 1265–1275.
10. Hales, Michael: Improving the Deadlift: Understanding Biomechanical Constraints and Physiological Adaptations to Resistance Exercise. *J. Strength Cond. Res.*, vol. 32, no. 4, 2010, pp. 44–51.
11. Fernandez-Gonzalo, Rodrigo, et al.: Muscle Damage Responses and Adaptations to Eccentric-Overload Resistance Exercise in Men and Women. *Eur. J. Appl. Physiol.*, vol. 114, no. 5, 2014, pp. 1075–1084.
12. Cole, Michael: Keeping Fit in Space a Real Workout for NASA Human Research Teams. 2016. <https://www.spaceflightinsider.com/missions/human-spaceflight/keeping-fit-in-space-a-real-workout-for-nasa-human-research-teams/> Accessed March 7, 2019.
13. Thompson, William K., et al.: Digital Astronaut Project Biomechanical Models: Biomechanical Modeling of Squat, Single-Leg Squat and Heel Raise Exercises on the Hybrid Ultimate Lifting Kit (HULK). NASA/TM—2015-218852, 2015. <http://ntrs.nasa.gov>
14. Escamilla, Rafael F., et al.: A Three-Dimensional Biomechanical Analysis of the Squat During Varying Stance Widths. *Med. Sci. Sports Exerc.*, vol. 33, no. 6, 2001, pp. 984–998.
15. Rajagopal, Apoorva, et al.: Full Body Musculoskeletal Model for Muscle-Driven Simulation of Human Gait. *IEEE T. Bio.-Med. Eng.*, vol. 63, no. 10, 2016, pp. 2068–2079.
16. Seth, Ajay, et al.: OpenSim: A Musculoskeletal Modeling and Simulation Framework for In Silico Investigations and Exchange. *Procedia IUTAM*, vol. 2, 2011, pp. 212–232.
17. Cohen, Jacob: *Statistical Power Analysis for the Behavioral Sciences*. Lawrence Erlbaum Associates, Hillsdale, NJ, 1988.
18. Batterham, Alan M.; and Hopkins, William G.: Making Meaningful Inferences About Magnitudes. *Int. J. Sports Physiol. Perform.*, vol. 1, no. 1, 2006, pp. 50–57.
19. Norrbrand, Lena; Pozzo, Marco; and Tesch, Per A.: Flywheel Resistance Training Calls for Greater Eccentric Muscle Activation Than Weight Training. *Eur. J. Appl. Physiol.*, vol. 110, no. 5, 2010, pp. 997–1005.
20. Norrbrand, L., et al.: Quadriceps Muscle Use in the Flywheel and Barbell Squat. *Aviat. Space Environ. Med.*, vol. 82, no. 1, 2011, pp. 13–19.







