Muscle Activation During Gravity-Independent Resistance Exercise Compared to Common Exercises

Björn A. Alkner; Daniel K.-I. Bring

INTRODUCTION: The aim was to study quadriceps muscle activation during resistance exercise using a flywheel device, developed as a gravity-independent resistance exercise device to be used during spaceflight, compared with traditional strength training exercises.

METHODS: Eight healthy men experienced in resistance exercise performed the following exercises in random order: flywheel leg press (FW), knee extension isokinetic dynamometry (ID), barbell front squat (FS), weight stack leg press (LP), and weight stack knee extension (KE). They accomplished eight repetitions of coupled concentric and eccentric actions with simultaneous recordings of surface electromyography (EMG) from the three superficial quadriceps muscles and knee angles using electrogoniometry. Maximal voluntary contraction (MVC) in knee extension was performed before and after these measurements.

RESULTS: EMG averaged across muscles and angles and normalized to MVC was 99/76% in FW, 48/41% FS, 65/47% LP, 81/52% KE, and 93/84% ID in concentric/eccentric phases, respectively. FW and ID showed higher mean EMG activity than LP and FS concentrically and higher than all other exercises eccentrically. No difference in activity between FW and ID was found. Pre- and post-MVC torque was comparable.

DISCUSSION: Quadriceps muscle activation was superior in FW and ID exercises compared to the other exercises. The difference was most pronounced in the eccentric phase, but even concentric activation was lower in traditional closed chain exercises. This data supports that FW is an effective training tool and should be considered when designing strength training programs for spaceflights and on Earth.

KEYWORDS: closed kinetic chain, countermeasure, electromyography, open kinetic chain, spaceflight.

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Participating in spaceflight missions leads to decreased muscle strength[18] and calls for effective countermeasures.[23,24] A flywheel device loads the muscles by the use of inertia of rotating flywheels,[9,10] works in microgravity in contrast to traditional strength training with weights, and has been proven to be effective as a countermeasure against strength loss during spaceflight simulation,[1,4,37] and also maintains the neuromuscular drive.[2] Moreover, it has been found to be efficient for strength training in adults[28,32,35] and the elderly[31] as well as for the prevention of muscle injury.[6] In contrast to barbell and weight stack devices, this specific gravity-independent flywheel device allows production of eccentric overload, i.e., higher eccentric than concentric force.[3,10,12] Performances of maximal or near maximal eccentric actions during resistance training are crucial to optimize muscle hypertrophy and increase muscle strength.[15,22] In traditional training modalities, the gravitational load is equal in the concentric and eccentric phase, and therefore maximal dynamic force production, which is greater during the eccentric phase,[21,38] is not achieved. It has also been shown that resistance exercise using traditional equipment does not result in maximal muscle activation, as measured with electromyography (EMG), during the concentric phase either.[5] Isokinetic actions, i.e., working at a constant

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angular velocity, have been shown to activate muscles more than exercise with barbell or weight stack devices during maximal effort.[25,26] However, isokinetic movements are rare in real life and have been shown to not correlate well with functional strength training performance[34,39] due to the principle of specificity.[27] In contrast, the flywheel device closer mimics the velocity changes seen in movements like lifting and jumping. In order to be prepared for return to Earth, these functional abilities are important to maintain during long-term space missions. Moreover, isokinetic devices may not be feasible on spaceflight missions as it, in contrast to the flywheel device, requires electricity.

Previous studies have indicated greater eccentric muscle activation when performing flywheel exercises compared to weight stack/barbell exercises in both open[29] and closed[30] chain exercises. Moreover, when comparing 5 wk of resistance exercise using knee extension devices employing either a flywheel or a weight stack device, the flywheel appeared to be more efficient in promoting muscle hypertrophy.[28] Hence, the possibility of this type of flywheel device to be more effective in activating muscles during resistance exercise, and the fact that it is working without gravity and electricity calls for more extensive studies comparing flywheels with other devices for resistance exercise.

The present study was designed to examine activation of the quadriceps muscles using five different exercises employing flywheel technology, isokinetic dynamometry, barbells, and weight stack machines and involving both open and closed chain exercises. We hypothesized muscle activation to be similar for all exercises in the concentric phase, but that the flywheel and isokinetic devices would produce greater eccentric EMG activity than the other devices.

METHODS

Subjects

Eight healthy men (28 ± 6 yr, 1.81 ± 0.06 m, 87 ± 8 kg), all experienced with resistance exercise, gave their informed consent to take part in the study. The protocol was approved by the regional ethical committee of Karolinska Institutet, Stockholm, Sweden.

Equipment

Leg press in a flywheel ergometer. The flywheel leg press ergometer (FW; YoYo Technology®, Stockholm, Sweden) has been described in detail elsewhere.[9–11] In brief, this device uses the inertia of a rotating flywheel(s) to provide resistance during both concentric and eccentric actions. By a pushing action (extending about the knee joint, concentric action, Con), the strap unwinds off the flywheel shaft and energy is imparted to the flywheels. The strap then rewinds by virtue of the energy of the rotating flywheels while the subject actively resists this action (eccentric action, Ecc). Subjects were requested to push with maximal effort through the entire range of motion. After gently resisting during the initial 20° of the subsequent eccentric action, maximal effort was then applied, aiming at bringing the wheels to a stop at 90° knee angle before initiating the subsequent cycle. Footplate position was adjusted according to leg length such that straight knees were avoided. Force was measured with the use of a strain-gauge in line with the footplate and connected to a data acquisition system described below. Subjects held with their hands on handle-bars situated beside the seat. In this study, two flywheels (diameter = 44 cm, 2.5 kg each) with the total inertia of 0.1105 kgm^2 were used for a total of eight repetitions.

Leg press in a weight stack machine. Bilateral leg press (LP) was performed using an incline sled apparatus (Nordic Gym®, Bollnäs, Sweden). Subjects laid in a supine position and the sled with the weight stacks traveled about 29 cm at a 55° inclination. Subjects were instructed to lower the weight until their knees reached 90° and were told to push (extending their knees) until near full extension. Hip angles ranged from 90 to 125° and subjects held with their hands on handle-bars situated beside the back seat. A 10-repetition maximum (10-RM) load, as titrated during the familiarization session, was used for a total of 8 repetitions.

Front squat. Front squats (FS) were performed using an Olympic barbell (Eleiko AB, Halmstad, Sweden). The barbell rested on the shoulders frontal to the neck and held by crossing the arms over the barbell. Subjects were instructed to descend to a 90° knee joint angle and rise up to almost full extension without locking the knees. A 10-RM load, as titrated during the familiarization session, was used for a total of 8 repetitions.

Knee extension in an isokinetic dynamometer. Bilateral knee extensions were performed using an isokinetic dynamometer (ID) (Speed-controlled Concentric Eccentric Extension Flexion) described in detail elsewhere.[36] Maximal concentric and eccentric repetitions were performed at $60° \cdot s^{-1}$ in the range from 90° knee joint angle to almost full extension at a hip angle of 115°. Shoulders, back, and thighs were strapped to the device and the arms crossed over the chest. Torque curves were produced on a strip-chart recorder (Gould 2400, Gould Inc., Cleveland, OH, USA) and were manually measured. The measurements of maximal voluntary contractions (MVC, isometric actions) were also performed using this device.

Knee extension in a weight stack device. Bilateral knee extensions (KE) were performed in a weight stack device (World Class®, Stockholm, Sweden) that used a cam system accommodating external torque through the range of motion. A 10-RM load, as titrated during the familiarization session, was used for 8 repetitions, performed from a 90° knee angle to full extension. The hip angle was 90°. Subjects held with their hands on handle-bars situated beside the seat.

Procedure

Electromyographic activity was measured from the three superficial quadriceps muscles during eight repetitions of coupled concentric and eccentric actions in the five different resistance exercises, emphasizing the knee extensor muscles and performed in a randomized order. The subjects were acquainted with the exercises during a familiarization session performed more than 1 wk prior to the testing session.

Electrode sites were marked and shaved for the vastus lateralis (VL), centralized between the trochanter major and patella, m. vastus medialis (VM), at 5 cm proximal to the patella, and m. rectus femoris (RF), centralized between the spina iliaca anterior inferior and patella, on the left leg. Subjects performed a 10-min submaximal cycle ergometer warm-up at a load of 1 kp. Electrode sites were then cleansed with alcohol and disposable bipolar Ag-Ag/Cl surface electrodes (Multi Bio Sensors Inc., El Paso, TX, USA) with 25-mm interelectrode distance were aligned in the direction of the muscle fibers. A reference electrode was placed over the tibial bone. An electrogoniometer was attached on the lateral side of the knee joint using adhesive tape and positioned by anatomical landmarks produced over the great trochanter, lateral epicondyle (center of the knee joint), and the lateral malleolus. MVC was then tested at 90° of knee flexion in the ID device. Two trials were allowed and if peak force differed more than 5%, an additional trial was performed. Subjects were asked to increase force smoothly and, after a plateau had been reached, maintain maximal force for about 3 s until halted by the investigator. Thereafter, eight repetitions of the five different exercises were performed in a randomized order. Between each exercise, 8 min of rest was allowed. Another test of MVC was performed at the end of the session to ensure that there was no decrease in force due to fatigue. The subjects were instructed not to perform heavy exercise the day before familiarization and test day and to avoid caffeine and nicotine intake prior to the sessions. The different exercises were performed as described under Equipment.

Raw EMG signals were amplified 600 times. The amplified raw EMG signal was filtered through a band-pass filter with low and high cut-off frequencies of 6 and 1500 Hz, respectively. The filtered signal was converted to an RMS signal using an AD536 circuit (Analog Devices Inc., Norwood, MA, USA) with an averaging constant of 100 ms. The converted signal was then sampled at 100 Hz together with angle and force (FW only) signals using a data acquisition system (MuscleLab™, Ergotest AS, Langesund, Norway[14]). EMG activity during MVC was established from the 1000-ms window showing the highest mean force. EMG activity during the concentric and eccentric actions was averaged over windows of 10° from 85° to 155° (ID 95°–155°, FW 85°–145°). If the lower or upper angle was not reached, data were averaged over existing angles. Data are averaged over three repetitions (numbers 3–5) in each set.

Statistical Analyses

Values presented are mean ± SD. In order to compare EMG activity across the different exercises, averaged over the whole range of motion, a repeated measures, two-factorial ANOVA (analysis of variance) was employed to detect EMG * Exercise interaction. If a significant interaction was seen, a Tukey's post hoc test was performed to detect differences between the different exercises. This was performed for the individual muscles as well as for the average of the three muscles. Statistical software Statistica™ (StatSoft, Inc., Tulsa, OK, USA) was used. Difference between pre- and post-MVC measurements and Con and Ecc peak force in FW were analyzed employing Students *t*-test. Statistical significance was set to $P < 0.05$ for all analyses.

RESULTS

The 10-RM weight (LP, FS, and KE), peak force (FW) and peak torque (ID, MVC) values are presented in **Table I**. There were no differences ($P = 0.15$) between pre- and post-MVC peak torque, indicating no fatiguing effect of the exercises performed. EMG activities during the different exercises are shown for the individual muscles and the mean for the three muscles in the concentric (**Fig. 1**) and eccentric (**Fig. 2**) phases. The reciprocal activation of the three muscles, normalized to EMG activity during MVC, is shown for the concentric and eccentric phases for each exercise in **Fig. 3**. Peak torque in FW was higher in the concentric compared to the eccentric phase ($P = 0.0013$).

The normalized EMG values averaged over all muscles and angles was 99% in FW, 65% in LP, 48% in FS, 93% in ID, and 81% in KE during the concentric phase and 76% in FW, 47% in LP, 41% in FS, 84% in ID, and 52% in KE during the eccentric phase. FW and ID showed greater mean EMG activity than LP and FS in the concentric phase and greater than all the other exercises in the eccentric phase. There was no difference in activity between FW and ID (for details, see **Table II**).

Activation of RF was higher in ID compared to LP ($P = 0.00051$) and FS ($P = 0.00014$) in the concentric phase and compared to all other exercises eccentrically. FW ($P = 0.0038$) and KE ($P = 0.0040$) produced greater RF activity concentrically compared to FS while not reaching statistical significance compared to LP ($P = 0.073$ and 0.077). FW produced greater RF activity eccentrically than LP ($P = 0.036$) and FS (0.0095). Activation of VM was greater in FW than in all other exercises except ID both concentrically and eccentrically ($P < 0.05$). Activation of VL was greater ($P < 0.05$) in FW compared to FS (Con: $P = 0.00053$, Ecc: $P = 0.0084$).

Table I. Average Torque, Force, and 10 RM Values.

10-RM WEIGHT	AVERAGE VALUE
MVC Pre, Peak Torque (Nm)	487 (98)
FW Con, Peak Force (N)	3527 (818)
FW Ecc, Peak Force (N)	2632 (7489)
LP, 10-RM load (kg)	245 (67)
FS,10-RM load (kg)	92 (26)
ID Con, Peak Torque (Nm)	349 (112)
ID Ecc, Peak Torque (Nm)	511 (145)
KE,10-RM load (kg)	43 (9)
MVC Post, Peak Torque (Nm)	452 (84)

Peak torque, peak force, and 10-RM weight values for the different exercises. Values are mean (SD) for eight subjects. MVC = Maximal voluntary contraction, isometric knee extension; FW = flywheel leg press; FS = front squat with barbell; ID = knee extension in an isokinetic dynamometer; KE = knee extension in a weight stack machine; LP = leg press in a weight stack machine; Con = concentric; Ecc = eccentric.

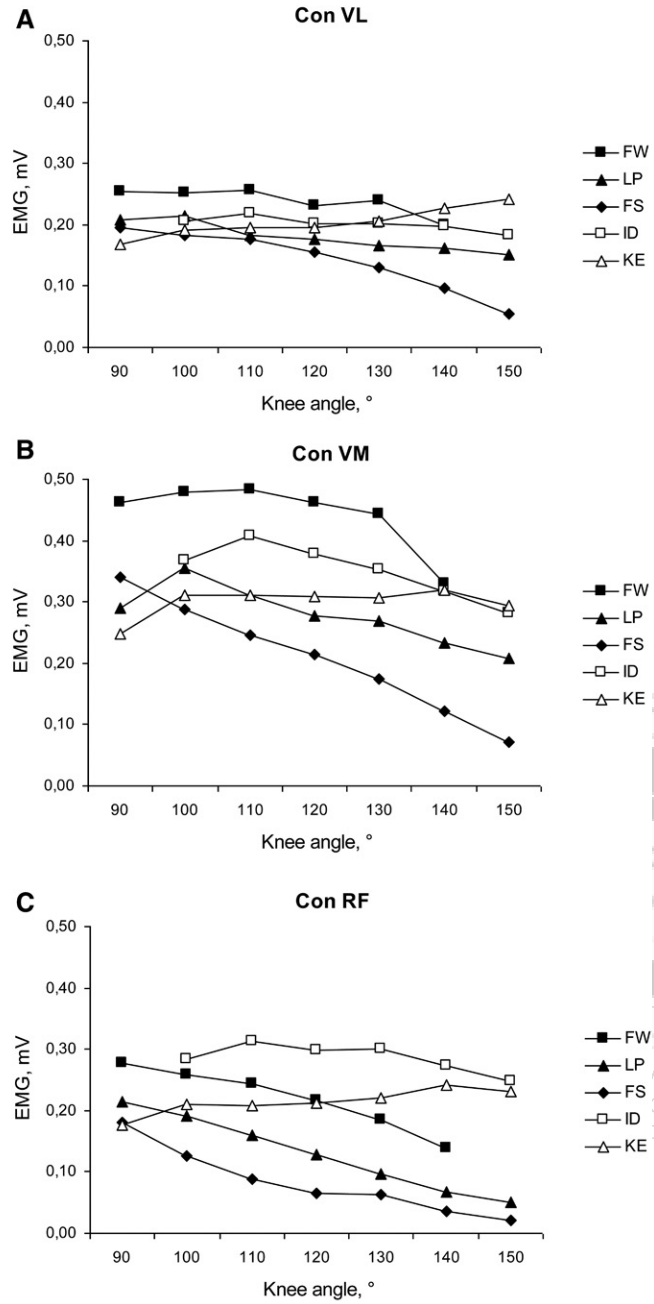

Fig. 1. EMG activity during the concentric (Con) phase of five different knee extensor exercises for the three superficial quadriceps muscles. A) VL = vastus lateralis, B) VM = vastus medialis, and C) RF = rectus femoris. Black square = flywheel leg press, black diamond = front squat with barbell, white square = knee extension in an isokinetic dynamometer, white triangle = knee extension in a weight stack machine, black triangle = leg press in a weight stack machine. Values are means for eight subjects.

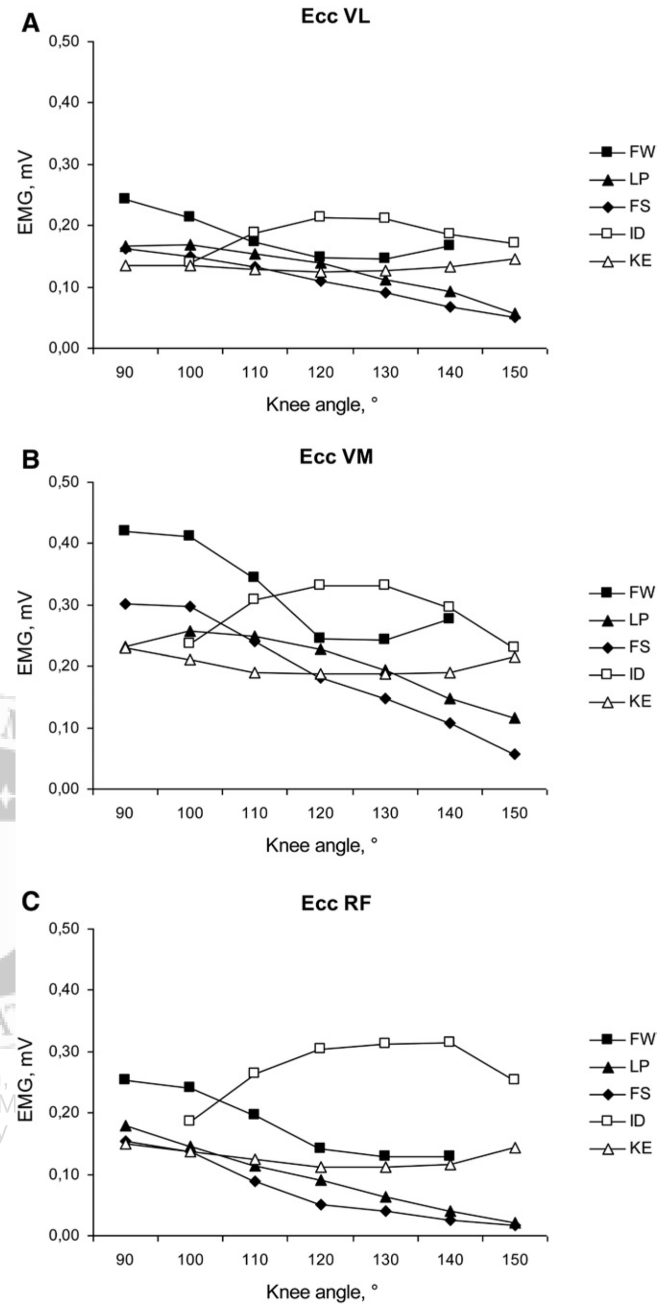

Fig. 2. EMG activity during the eccentric (Ecc) phase of five different knee extensor exercises for the three superficial quadriceps muscles. A) VL = vastus lateralis, B) VM = vastus medialis, C) RF = rectus femoris. Black square = flywheel leg press, black diamond = front squat with barbell, white square = knee extension in an isokinetic dynamometer, white triangle = knee extension in a weight stack machine, black triangle = leg press in a weight stack machine. Values are means for eight subjects.

DISCUSSION

The present study examined quadriceps muscle activation during five different open and closed kinetic chain exercises. Our data revealed that training using flywheel technology and isokinetic dynamometry induced higher degrees of eccentric muscle activation compared to traditional devices like barbells or weight stack devices. Even concentric FW and ID were superior to the traditional closed chain exercises. Contrasted to previous studies comparing quadriceps muscle activation using flywheel and traditional gravity-dependent devices,[29,30] the present study used another flywheel modality (seated leg press) and compared not only with one but with four other common exercises.

From the present data, it is evident that eccentric EMG amplitude, as hypothesized, was higher in FW and ID than in the other exercises. It has to be emphasized that when

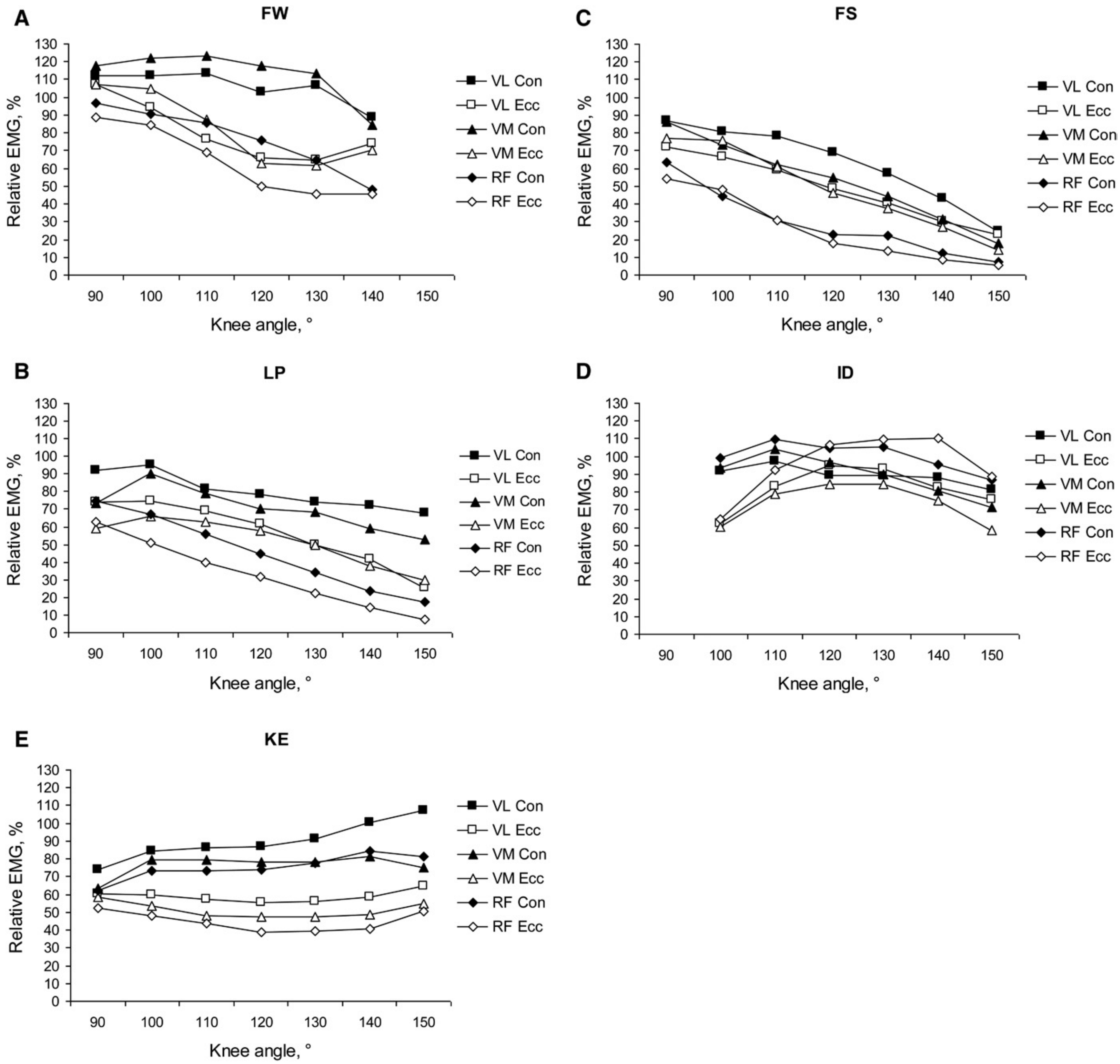

Fig. 3. Relative EMG activity, normalized to amplitude during MVC, for the three superficial quadriceps muscles during the concentric (Con) and eccentric (Ecc) phase of five different knee extensor exercises. A) flywheel leg press (FW); B) leg press in a weight stack machine (LP); C) front squat with barbell (FS); D) knee extension in an isokinetic dynamometer (ID); E) knee extension in a weight stack machine (KE). Black square = vastus lateralis Con, white square = vastus lateralis Ecc; black triangle = vastus medialis Con, white triangle = vastus medialis Ecc; black diamond = rectus femoris Con, white diamond = rectus femoris Ecc. Values are means for eight subjects.

performing the FW exercises, muscles are at rest during the early eccentric phase before initiating maximal effort, while they work maximally during the entire range of motion in ID. Although averaged over the complete range of motion, mean EMG amplitude was significantly higher in FW than in the standard exercises. Moreover, when performing maximal effort at lower knee angles (Fig. 2), EMG was of much greater amplitude in FW than in the gravity-dependent exercises. It is also worth mentioning the rapid increase in EMG activity between 120–100° in FW during the eccentric phase (Fig. 2), indicating a fast force development within the quadriceps muscle mimicking a functional deceleration. The fact that peak force was higher concentrically than eccentrically in FW (Table I) is explained by the fact that muscles are in rest eccentrically, but are working maximally concentrically at greater knee angles, where you can develop highest force in a leg press device. However, the high eccentric activation suggests a high tension on the muscle, beneficial for development of muscle hypertrophy and increase in muscle strength.[15,22]

Also in the concentric phase, mean EMG amplitude was higher in FW and ID compared to the traditional closed kinetic chain exercises. Several factors may be part of the explanation.

Table II. Post Hoc Test Values.

ECC	CON				
	FW	**LP**	**FS**	**ID**	**KE**
FW		0.0046*	0.00016*	0.92	0.19
LP	0.0071*		0.37	0.033*	0.48
FS	0.0019*	0.98		0.00042*	0.013*
ID	0.77	0.00045*	0.00020*		0.60
KE	0.038*	0.96	0.74	0.0022*	

P-values from Tukey's post hoc test for comparisons between the different exercises for values that are mean across angles and muscles. Values in upper right corner represent concentric EMG activity, values in lower left corner represent eccentric EMG activity. *F*-values: Con: 10.86; Ecc: 11.60. Degrees of freedom: 28. *Denotes statistical significance ($P < 0.05$). FW = flywheel leg press; FS = front squat with barbell; ID = knee extension in an isokinetic dynamometer; KE = knee extension in a weight stack machine; LP = leg press in a weight stack machine; Con = concentric; Ecc = eccentric.

In FW and ID, subjects can perform maximally during the entire concentric phase. Due to changes in muscle length and biomechanical conditions during performance in the traditional closed kinetic chain exercises, the weight that can be lifted is limited by the angles of the range of motion when the ability to produce torque is lowest. This becomes evident by the marked decrease in muscle activation when the knee is extended and thus in the range of mechanical advantage, meaning that the load is submaximal during this part of the movement.[20,21] Moreover, subjects can perform maximally in every repetition in FW and ID. In the traditional exercises the load is limited to the 10-RM weight determined in advance, meaning that the load will be submaximal during most of the repetitions of the set. It can further be speculated that performing the traditional exercises requires a more controlled approach compared to the all-out effort applicable in the FW and ID devices.

Mean EMG amplitude yielded during the concentric phase in the open kinetic chain exercise KE, was not significantly lower than in FW and ID. This may be explained by the fact that muscle activation is maintained over the full range of motion in opposition to the gravity-dependent closed chain exercises, as also shown previously.[5,16] This is supported by the study of Norrbrand et al.,[29] who showed no difference in concentric but in eccentric EMG when comparing knee extension devices employing flywheel or weight stack loading. In this context it has to be stressed that open chain exercises like jumping have shown less increase in functional performance compared to closed chain exercises.[13]

The greater muscle activation in the flywheel exercises compared to squat exercise shown in this study was supported by MRI measurements in the study by Norrbrand et al.,[30] who failed to show such a significant difference using EMG. However, that study was designed with MRI as primary outcome from performing exercises during different days and inducing fatigue by performing five sets. They were using a different flywheel device compared with the present study. These factors may explain why the EMG results differ between the studies. Altogether, data on flywheel exercise imply greater muscle activation compared to closed chain exercises using weights.

The actions performed in ID produced mean EMG amplitudes equal to FW. In similarity with FW, ID allows the generation of maximal force in every repetition and during the entire range of motion. A major concern regarding isokinetic actions is that the movements are not functional, as the angular velocity is constant throughout the range of motion. Due to the principle of specificity, the implementation of contraction velocities similar to actual performance is of crucial importance when designing strength training programs for spaceflight, sports, or rehabilitation.[4,27] This is supported by the fact that resistance training programs producing marked hypertrophy and increases in the weight that can be lifted can promote no or a minute increase in maximal isokinetic torque.[34,39] Flywheel training better mimics functional movements and could, therefore, be more beneficial than isokinetic training. A weakness of the design of the present study is that FW was performed as a closed chain and ID as an open chain exercise only, but a more extensive test protocol might have been too fatiguing.

The relative activation of RF was less in the multijoint actions (FW, LP, FS) compared to single-joint actions (ID, KE), especially in angles close to knee extension, which is consistent with previous EMG[8,17,40] and MRI[19] studies. The lesser activity of RF can be explained by the hip flexor function of this muscle, which is opposing the hip extension movement in the leg press and squat exercises.[40] However, FW produced higher RF activation than the other closed kinetic chain exercises, in accordance with the study by Norrbrand et al.[30]

Previous studies have shown lower EMG activity eccentrically compared to concentrically, even if higher torque is produced,[21,38] explained by lower metabolic cost eccentrically.[7] In the present study, lower eccentric EMG activity was obvious for the exercises with equal load concentrically and eccentrically. Even in FW and ID, eccentric EMG activation was less than the concentric, but closer to maximal activation than in the other exercises.

In summary, this study emphasizes the beneficial features of flywheel training and supports previous training data[28,33,35] in that the flywheel device can be an important asset in the exercise arsenal in order to improve muscle size and strength. As the flywheel device, in contrast to the traditional weight-based devices tested, is gravity-independent, it can be an important tool for preventing muscle loss during space missions. Future studies may further investigate the efficacy compared to other devices during simulated and real spaceflight.

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