Eur J Appl Physiol (2007) 101:697–703
DOI 10.1007/s00421-007-0548-y

ORIGINAL ARTICLE

Comparison of conventional resistance training and the fly-wheel ergometer for training the quadriceps muscle group in patients with unilateral knee injury

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Accepted: 2 August 2007 / Published online: 24 August 2007

Abstract A fly-wheel ergometer (FWE) offering resistance training of the knee extensors has been designed for space travel and found to be effective during bed rest. The possibility exists that this device is also effective in training the knee extensors after knee injury. The purpose of this study was to compare the FWE to standard knee extensor training equipment for their effects on individuals with a history of knee injury, a group who commonly suffer from weakness of the knee extensors that effects their function. Twenty-nine subjects completed the study, which included tests of knee self-assessment, knee extensor static and dynamic muscle strength, size and neural activation as well as single leg power output, standing balance and vertical jump performance. Both groups showed statistically significant ($P < 0.05$) improvements in these variables over the 3-month training period but no differences were noted between the groups. The FWE appears to be as effective as standard resistance training equipment for improving knee extensor muscle group size and performance after knee injury.

Keywords Knee extensors · Strength training · Muscle size · Vertical jump · Muscle performance · Rehabilitation

Introduction

Knee injuries are common, particularly in amateur and professional sports people. Regardless of whether surgical intervention is used, these individuals are likely to undergo a period of rehabilitation, with resistance training of the quadriceps muscle group one of the fundamental aspects of this training. This type of training is common because the knee extensors suffer such great losses in strength and size as a consequence of a variety of knee injuries (Holder-Powell and Rutherford 1999). These losses are long lasting (Rutherford 1998; Holder-Powell and Rutherford 1999) and deleterious to leg function (Holder-Powell and Rutherford 2000). Despite this common rehabilitation focus, weakness of this muscle group has been found to persist after completion of "standard" rehabilitation (Holder-Powell and Rutherford 1999, 2000; Rutherford 1998).

Quadriceps training after knee injury is usually performed on devices where resistance is, generally, constant through the range of motion (ROM). These devices do not offer resistance to match the torque producing capacity of the muscle group (Hooper et al. 2002), except near the weakest point(s) in the range, and are especially inadequate during the eccentric phase of the movement. The possibility exists that use of a device such as a fly-wheel ergometer (FWE), which offers inertial resistance and is designed to offer challenging resistance throughout the ROM during both concentric and eccentric contractions, will be superior in increasing quadriceps strength and knee function in rehabilitation. The device has been shown to be effective in promoting muscle hypertrophy and strength increases in individuals undergoing prolonged bed rest (Trappe et al. 2004). The rehabilitative potential of this type of equipment, designed for resistance training in space, has not been compared to more traditional equipment. The purpose of this study was to investigate whether neuromuscular adaptations and self-perceived knee function following conventional resistance and FWE training differ after knee injury. We hypothesise that the FWE device will offer superior training

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due to its ability to offer strong resistance through the range of motion, especially during eccentric contraction.

Methods

Subjects

The target number of subjects in this study was 30 requiring the recruitment of 40 subjects to account for dropout. Subjects were considered for inclusion in the study if they had a history of unilateral knee injury. Potential subjects came from 3 sources in the London metropolitan area: (1) patients undergoing knee rehabilitation in the outpatient physiotherapy department at St Thomas's Hospital; (2) employees of St Thomas's Hospital; and (3) employees of King's College London. Ethical permission for this study was granted by King's College London.

Testing

Subjects gave written informed consent and were tested immediately before, at the midpoint, and immediately after a 3 month training programme by an examiner not blinded to subject group. Outcome measures were: (1) self-assessed knee function (using the Hughston Clinic questionnaire); (2) vastus lateralis cross sectional area (using ultrasound); (3) isometric and dynamic quadriceps strength at 0, 60 and 180°/s (concentric for both dynamic tests, eccentric for 60°/s); (4) quadriceps inhibition using twitch superimposition; (5) injured and uninjured single leg stance balance using the Balance Platform (Cosmogramma, Italy); (6) injured and uninjured leg extensor power using the Nottingham power rig; and (7) injured and uninjured single leg vertical jump maximal performance. All of these tests were performed at baseline, midway and on completion of the 12 week exercise intervention, with the exception of the muscle cross-sectional area, which was only performed at baseline and on the final assessment.

Cross-sectional area of the vastus lateralis muscle was tested first. Subjects were initially positioned on a treatment plinth in the supine position for 30 min during which time they were asked to relax completely and perform no muscular effort with their lower limbs. This was to ensure that the volume of the skeletal muscle returned to resting levels, as described by Reeves et al. (2004). The distance between the lateral tip of the greater trochanter and the lateral joint line of the right knee was then measured and divided by three to render a value of × cm. A temporary line was then marked on the subject × cm proximal to the lateral joint line. This ultrasound guideline, one-third of the distance from the knee lateral joint line to the greater trochanter, was marked transversely around the thigh between the lateral border of the rectus femoris and the lateral border of the biceps femoris. An identical line was then replicated on the left leg using the same parameters. Distance × was recorded to standardise subsequent measures.

A 7.5 MHz linear ultrasound head, 7.5 cm long (Aloka SSD-900, Tokyo, Japan) was run slowly over the vastus lateralis along the marked line from anterior to posterior and the image recorded on a digital camera. This was repeated for both legs and the images subsequently downloaded to a secure storage medium. During analysis, separate frames were selected from the digital images and composed using Adobe Photoshop software (Adobe, San Jose, USA) to form a single panoramic image of the vastus lateralis. From this image linear variables were calibrated and cross sectional area was measured using Scion software (Scion Corporation, Frederick, MD, USA). This technique has been developed and validated by Reeves et al. (2004) who demonstrated an intra-class correlation coefficient for the CSA of the vastus lateralis of 0.998 when compared with magnetic resonance imaging.

The *Hughston Clinic questionnaire* was used to evaluate the patient's self-assessment of their knee condition (Flandry et al. 1991) and scoring was performed as described elsewhere (Hooper et al. 2001). The final score was calculated by aggregating the scores of the questions answered and converting to a percentage of the maximum possible score of the questions answered. A perfect knee would score 0 with 100% being the worst possible score.

Isokinetic strength measurements were completed on the Kin-Com isokinetic dynamometer (Chattanooga group, Version 5.16, Chattanooga, USA). The uninjured leg was always tested first at a test velocity of $60°s^{-1}$ for concentric and eccentric contractions and then at $180°s^{-1}$ for concentric contractions. The testing range of motion was from 80° to 10° knee flexion. These angles were selected to ensure maximum subject safety and comfort. Subjects were allowed several sub-maximal test contractions to familiarise themselves with the machine. All subsequent tests were done with the subject stabilised at the pelvis with a lap strap and their arms folded across their chest. Recording began following a 2 min rest period after the cessation of the practice. During testing subjects were encouraged to extend their knee as hard and as fast as they could. No verbal reinforcement was given during the contractions in an attempt to standardise the test protocol. Visual reinforcement was given in that the subject had a clear view of the Kin Com monitor during testing, which displayed the trace of their best previous contraction. Subjects were encouraged to improve on this result prior to the initiation of each contraction. Testing was temporarily stopped when the subject failed to better their previous result on two consecutive contractions. At this point the subject was given a 30 s rest and asked to repeat the contraction again. This was to ensure that the recorded result reflected their maximum effort as accurately as possible. On completion of the concentric and eccentric testing at $60°s^{-1}$ the subject was allowed a break of not greater than 3 min during which time the Kin Com was reconfigured to record data at the faster testing velocity of 180°s^{-1}. Subjects were only required to perform concentric contractions at this velocity. These contractions were repeated in a similar manner to that described above until a peak force that could not be surpassed was achieved. Following a rest period of approximately 5 min, during which the examiner reconfigured the Kin Com, the testing protocol was repeated for the affected knee at both velocities, in an identical manner.

Central neural activation was assessed using the *twitch superimposition technique* (Rutherford et al. 1986). Two electrodes (8 × 12 cm) were placed inside moistened reuseable covers. These were then fixed with elastic bandages to the anterior thigh of the subject approximately one-third and two-thirds of the distance between the anterior superior iliac spine and the superior border of the patella. The subjects were seated on the Kin Com with the knee fixed at 80° flexion and their arms and pelvis stabilised as before. The subject then performed an isometric maximal voluntary contraction (MVC) and a horizontal cursor was placed on the recording screen at a height that represented 10% of the MVC height. Electrical pulses (1 Hz, pulse duration 200 μs) of progressively increasing intensity were then passed through the electrodes via a stimulator (Digitimer DS7, Welwyn Garden City, UK) until a muscular contraction in the quadriceps was elicited. This current was gradually increased until the twitch height reached the horizontal line that represented 10% of the subject's MVC or the subject refused to allow a further increase in intensity. This intensity was recorded and the stimulation temporarily halted whilst the subject was prepared for the active part of the test.

Three resting twitches were then recorded before the subject performed a series of 3 isometric MVC's whilst the current, at the pre-determined intensity, was passed through the electrodes. Each MVC lasted 3–4 s interspersed with rest periods of 3 s. Recording and subsequent analysis of this data was carried out with the appropriate software (Signal version 2.14, Cambridge, UK). Inhibition was calculated as the superimposed twitch height as a percentage of the resting twitch.

Standing balance was assessed on the balance platform (Churchill Medical Ltd, Cosmogramma, Italy). Subjects were asked to perform single leg standing for 30 s with their eyes open and their arms folded across their chest. During this time they were asked to attempt to stand as still as possible and were offered no verbal or visual cues to assist them. This process was repeated 3 times and the mean value of the three tests for each leg was used in the subsequent analysis. The balance platform provides a measure of path length, which represents the distance that the subjects' centre of gravity translates from its initial start point during the 30 s trial. In this test, the longer the path length, the poorer the subject's standing balance. The right leg was tested first followed by the left leg.

The power rig (Leg Rig Analysis, version 3.3, Nottingham, UK) provides a measure of the *peak power* generated by the lower limb during a hip and knee extension movement (Bassey and Short 1990). Subjects were seated on the rig and the seat was adjusted until the knee was in 10° flexion with the foot plate completely depressed. This distance was recorded to ensure reproducibility on subsequent tests. The footplate was then raised thus flexing the knee and the resistance wheel aligned via the viewing aperture. The subject was then instructed to push the pedal down to the floor as hard and as fast as possible. The peak power (W) was recorded and the procedure repeated until the subject failed to better their score on two consecutive occasions. The uninjured leg was always tested first.

Subjects performed the *single leg vertical jump test* on the uninjured side first. The test was performed with shoes on and subjects were allowed to land on two legs to reduce the risk of injury. Subjects repeated maximum effort jumps until there were two consecutive reductions in the height jumped. This method was based on the belief that no further gains would be made through practice and further reductions would occur due to pain or fatigue. The maximum height achieved was used in later analysis.

During this testing, subjects stood at a right angle to the wall reaching as high as they could with their feet flat on the floor marking the wall with the tip of their chalked middle finger. This represented the baseline height. The subject then jumped as high as they could, re-marking the wall at the highest point of the jump. The distance between the baseline and the highest chalk mark was considered the maximum height jumped (Perry et al. 2005).

Training

Subjects were randomly assigned to the fly wheel (YoYo® Technology Inc., Stockholm, Sweden) or standard (knee extension/hamstring curl machine, Health and Leisure, Walthamstow, UK) training groups. Subjects were asked to attend supervised training sessions at one of two sites (St Thomas's Hospital and King's College London) three times per week for 3 months with supervision at both sites by the examiner. Both groups trained only the quadriceps of their injured leg and each session consisted of four sets of ten repetition maximums. The velocity of the fly wheel resistance device, which is relatively consistent between subjects, was matched for the standard training by use of a metronome set at 1 beat/s where subjects were encouraged to raise the weight/move the flywheel over 3 beats and lower it at the same rate, giving an angular velocity of 30°/s for both the concentric and eccentric phases. Rest periods of no less than 1 min were given between sets.

Statistics

ANOVA was used to evaluate for statistically significant differences due to group and test stage (pre-, mid- and post-test).

Results

Twenty-nine subjects successfully completed the study, i.e. attended the pre- and post-test. Table 1 is a summary of their self-reported knee diagnoses. The number of training sessions attended over the entire trial was similar for both groups with the FWE group attending an average (SD) of 19 (5) sessions and the MG group attending 22 (9). For the standard group, the mean (SD) starting training load was 1.65 kg (2.14) and the final load, used in the last training session, was 6.75 kg (4.62).

Table 1 Self-reported knee injury diagnoses in the two training groups

Knee diagnosis	Group fly wheel ($N = 15$)	Group standard ($N = 14$)
Anterior cruciate ligament deficiency	2	2
Anterior cruciate ligament reconstruction	1	1
Anterior knee pain syndrome	2	0
Benign tumour	0	1
Iliotibial band friction syndrome	1	0
Medial collateral ligament injury	2	1
Meniscal injury	3	3
Posterior cruciate ligament deficiency	1	0
Quadriceps femoris tear	0	1
Unknown	5	7

Some of the study participants had more than one diagnosis

Observing the pre-test results in Table 2, the data indicates that the training groups were well matched, the only significant difference being in quadriceps inhibition with the standard group showing less inhibition at baseline.

Table 2 also displays the injured leg deficiencies, which can be defined as injured/uninjured ratios of ≤90%. Both groups displayed deficiencies in knee extensor strength in all modes of contraction. The twitch results also indicate knee extensor inhibition in both groups. Finally, both groups had an approximate 10% loss in vastus lateralis muscle cross-sectional area.

Tables 3 and 4 contain the mid- and post-test results and no statistically significant ($P < 0.05$) differences were found between the groups. These tables also display the variables in which each group exhibited statistically significant ($P < 0.05$) differences from pre-test results and between mid- and post-tests. The training groups exhibited improvement in the same six (out of ten) outcome variables over the 3-month training period. Of these variables, knee extensor concentric strength at 60°/s and eccentric strength are arguably the most specific to the training used in this study, so additional detail about performance in these tests is offered in Figs. 1 and 2.

As indicated in Table 4, most of the injured/uninjured ratios were normalised (i.e. >90%) by the end of training in

Table 2 Pre-test results in the two training groups

Variable	Group fly wheel ($N = 15$)			Group standard ($N = 14$)		
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum
Gender	9 male, 6 female			7 male, 7 female		
Age	38 ± 12	21	59	41 ± 15	20	64
BMI (kg/m^2)	23 ± 4	19	33	24 ± 6	18	38
Injury chronicity (months)	87 ± 2	3	275	139 ± 124	3	345
T1 Hughston knee self-assessment (0–100, lower score = better knee)	0.26 ± 0.15	0.02	0.60	0.25 ± 0.20	0.05	0.68
T1 Balance I/U ratio	1.22 ± 0.61	0.75	3.28	1.15 ± 0.51	0.63	2.60
T1 concentric quads I/U 60°/s	0.89 ± 0.10	0.71	1.03	0.91 ± 0.16	0.63	1.37
T1 eccentric I/U 60°/s	0.83 ± 0.16	0.54	1.18	0.85 ± 0.15	0.46	1.11
T1 concentric I/U 180°/s	0.90 ± 0.12	0.72	1.17	0.89 ± 0.22	0.33	1.35
T1 I/U isometric	0.89 ± 0.13	0.63	1.18	0.90 ± 0.16	0.64	1.17
T1 twitch I/U*	0.70 ± 0.17	0.46	1.02	0.85 ± 0.21	0.61	1.40
T1 power rig I/U	0.94 ± 0.20	0.52	1.44	0.88 ± 0.21	0.61	1.28
T1 vertical hop I/U	0.84 ± 0.13	0.50	1.06	0.96 ± 0.28	0.60	1.50
Vastus lateralis CSA I/U	0.91 ± 0.16	0.39	1.11	0.90 ± 0.14	0.69	1.16

T1 test 1 (baseline, aka pre-test), *I/U* injured/uninjured ratio

* Statistically significant difference between groups, $P = 0.05$

Table 3 Mid-test results in the two training groups

Variable	Group fly wheel (*N* = 15)			Group standard (*N* = 14)		
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum
Period T1-T2 (days)	56 ± 7	42	70	53 ± 10	43	79
T2 Hughston knee self-assessment (0–100)	0.20 ± 0.16*	0.02	0.63	0.21 ± 0.21*	0.02	0.65
T2 Balance I/U ratio	1.26 ± 0.65	0.80	3.46	1.02 ± 0.24	0.69	1.49
T2 Concentric quads I/U 60°/s	0.93 ± 0.12	0.74	1.11	0.93 ± 0.14	0.75	1.29
T2 Eccentric I/U 60°/s	0.97 ± 0.17	0.80	1.40	0.92 ± 0.15	0.69	1.20
T2 Concentric I/U 180°/s	0.90 ± 0.14	0.66	1.14	0.92 ± 0.12	0.70	1.21
T2 I/U Isometric	0.96 ± 0.23**	0.67	1.60	0.95 ± 0.15**	0.68	1.14
T2 Twitch I/U	1.01 ± 0.44	0.66	2.42	1.05 ± 0.54	0.28	2.78
T2 Power rig I/U	1.01 ± 0.12***	0.79	1.25	0.91 ± 0.11***	0.75	1.15
T2 Vertical hop I/U	0.90 ± 0.16	0.60	1.22	1.05 ± 0.36	0.69	2.00

The training groups did not exhibit any statistically significant ($P < 0.05$) differences

T2 test 2 (6 weeks into 12 week intervention, aka mid-test), *I/U* injured/uninjured ratio

* Statistically significant difference from pre-test ($P < 0.01$)

** Statistically significant difference from pre-test ($P = 0.028$)

** Statistically significant difference from pre-test ($P = 0.045$)

Table 4 Post-test results in the two training groups

Variable	Group fly wheel (*N* = 15)			Group standard (*N* = 14)		
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum
Period T1-T3 (days)	101 ± 13	77	127	101 ± 13	84	128
Training sessions attended	19 ± 5	12	29	22 ± 9	6	37
T3 Hughston knee self-assessment (0–100)	0.16 ± 0.14**+	0.02	0.53	0.18 ± 0.21**+	0.00	0.63
T3 Balance I/U ratio	1.08 ± 0.31	0.67	1.88	0.99 ± 0.23	0.64	1.36
T3 concentric quads I/U 60°/s	1.05 ± 0.25	0.69	1.55	0.98 ± 0.19	0.80	1.37
T3 eccentric I/U 60°/s	1.11 ± 0.27**	0.65	1.57	1.02 ± 0.14**	0.83	1.27
T3 eoncentric I/U 180°/s	1.04 ± 0.32	0.64	1.74	0.88 ± 0.19	0.54	1.12
T3 I/U Isometric	1.07 ± 0.26***	0.51	1.56	1.15 ± 0.29***	0.67	1.73
T3 twitch I/U	1.16 ± 0.26**	1.00	2.00	1.07 ± 0.39**	1.00	2.00
T3 power rig I/U	1.03 ± 0.17**	0.77	1.44	1.05 ± 0.12**	0.85	1.25
T3 vertical hop I/U	0.96 ± 0.15	0.57	1.30	0.92 ± 0.25	0.48	1.36
Vastus lateralis CSA I/U	1.06 ± 0.21**	0.52	1.51	1.09 ± 0.16**	0.89	1.52

The training groups did not exhibit any statistically significant ($P < 0.05$) differences

T3 test 3 (after the 12 week intervention, aka post-test), *I/U* injured/uninjured ratio

* Statistically significant difference from pre-test ($P < 0.05$)

** Statistically significant difference from pre-test ($P < 0.01$)

*** Statistically significant difference from pre-test ($P = 0.032$)

+ Statistically significant difference from mid-test ($P = 0.02$)

both groups with supranormal (>100%) performance in many of these.

Discussion

Both training groups exhibited significant increases in strength and muscle size during the training period. The first consideration in comparing the training results in the two groups is whether the groups' baseline performances differed. Reviewing Table 2, possible differences between groups may have existed for the following variables where the standard group may have been superior at baseline: (1) standing balance; (2) quadriceps inhibition (this was the only variable where a statistically significant difference was found between the groups); and (3) vertical jump. Additionally,

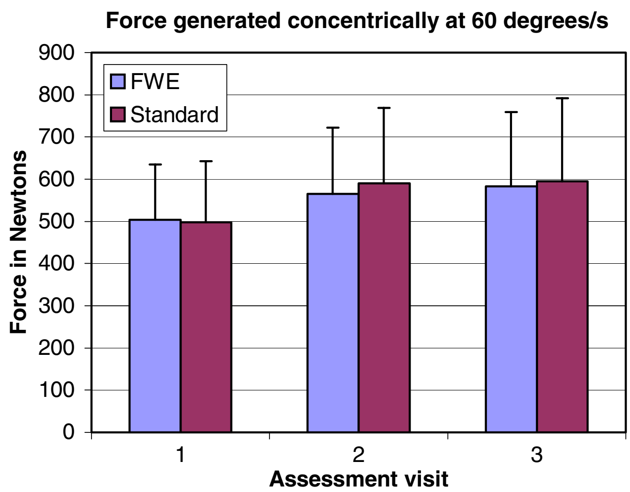

Fig. 1 Knee extensor performance of injured leg in isokinetic testing in the flywheel ergometer (*FWE*) and standard training groups

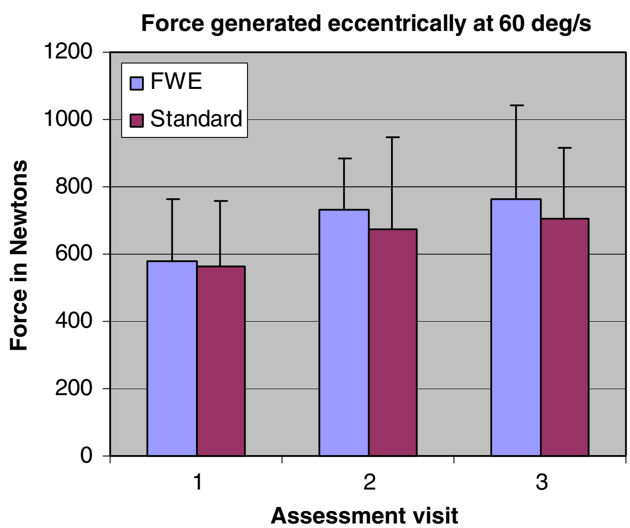

Fig. 2 Knee extensor performance of injured leg in isokinetic testing in the flywheel ergometer (*FWE*) and standard training groups

the standard group possibly had longer-standing injuries and it could be argued that this either made them more amenable to rehabilitation or, conversely, limited their rehabilitation progress. The FWE group had higher (i.e. better) baseline scores for the leg power test. We have taken these mixed results to be indicative of relatively equal matching, especially since the groups were so similar for baseline static and dynamic quadriceps strength.

It is clear from Table 4 that the interventions were effective, assuming that without training the groups would have not exhibited changes. These results indicate that both groups exhibited comprehensive improvements in performance with the standard exercise group showing statistically significant changes in all the same variables exhibited by the FWE group. This is surprising for the twitch results as the FWE group had statistically greater inhibition at baseline compared to the standard training group. Despite this greater inhibition the FWE group clearly were able to train as effectively as the standard group.

The main purpose of this study was to evaluate whether the effectiveness of the FWE training device differs from standard quadriceps exercise equipment in rehabilitation of individuals with chronic knee injuries. The findings appear to be clear—the devices are equally effective. This is surprising, given the difference in sensation one feels when using the two machines. The FWE feels like it is better at offering strong resistance through the range of motion, similar to what occurs during isokinetic resistance exercise. This is especially notable in the eccentric phase of the exercise where the sensation of resistance on the standard equipment is less than during the concentric phase. It is possible that the FWE does offer superior resistance eccentrically but that this difference is not great and this appears to be borne out by the results in this study where the eccentric quadriceps injured/uninjured ratios increased from 0.83 to 1.11 in the FWE group and from 0.85 to 1.02 in the standard group. The possibility also exists that the FWE is superior in eccentric training but that a longer training period is needed to exhibit its superior effects, as partly shown by the significant improvement from mid- to post-test indicating that improvements in performance were still occurring when training was terminated. Conversely, the injured/uninjured ratios indicate that the ceiling for improvement might be close after three months of training. Finally, it is also possible that the close supervision of subjects in the standard training group prevented these subjects from avoiding full eccentric training that we suspect is common in unsupervised training where individuals are likely to have a tendency to lower the weight at a faster rate.

One of the most impressive results in this study is the large amount of hypertrophy exhibited in the vastus lateralis in both groups. The injured/uninjured ratio before training was approximately 90% in both groups and this improved to 106 and 109% in the FWE and standard groups, respectively, by the end of training. We know of no other investigations of whole muscle size responses to resistance training after knee injury.

As mentioned in the previous paragraph relative to the possible effect of training termination on finding differences between groups, the possibility exists that training with the FWE might be superior but this superiority went undetected in this study. With this in mind it is important to consider which possible factors need to be considered in planning future studies of this nature. The fundamental questions here are: was the training of the correct type in terms of, for example, what occurred in each session? Were the correct outcomes measured and at the right times? In terms of both of these, one might be concerned that the training was not applied over a long enough period. But closer analysis of the results in Table 4 indicate that a ceiling was being approached after three months of training for most of the outcomes with, generally, further improvement only likely for self-assessed knee function and vertical hop performance. As for the outcomes measured, if the devices differ in their effectiveness during the eccentric portion of the exercise, it would have been more useful to have included a functional task that challenges the eccentric force capacity of the knee extensors more than the vertical jump as employed in this study. One possibility would have required that landing during this testing be done unilaterally and this might be even more useful for a horizontal hop where the subject could be required to "stick" the landing.

One of the main limitations of this study is its possible limited generalisability to clinical practice. Many of the subjects in this study only trained their quadriceps during the intervention period while the typical programme that would be used would consist of resistance training of other muscle groups plus stretching and functional activity exercises. But this limitation can be seen as an attribute as the changes noted are likely to be largely due to the quadriceps resistance training used. Another related limitation is the inclusion of individuals who were not suffering from notable quadriceps weakness as noted in the maximum values listed in Table 2. We suspect that neither of these limitations affects the primary conclusion of this study, that FWE is equally effective in training the quadriceps as standard equipment for individuals with a variety of chronic knee problems.

Acknowledgments The authors thank the European Space Agency for funding this study.

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