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Neuromuscular and balance responses to flywheel inertial versus weight training in older persons

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ABSTRACT

Aim: Loss of muscle strength and balance are main characteristics of physical frailty in old age. Postural sway is associated with muscle contractile capacity and to the ability of rapidly correcting ankle joint changes. Thus, resistance training would be expected to improve not only strength but also postural balance.

Methods: In this study, age-matched older individuals (69.9 ± 1.3 years) were randomly assigned to flywheel ($n = 12$), or weight-lifting ($n = 12$) groups, training the knee extensors thrice weekly for 12 weeks. The hypotheses were that owing to a larger eccentric loading of the knee extensors, flywheel training would result in (a) greater gains in quadriceps strength; (b) greater improvements in balance performance compared with weight-lifting training. Isokinetic dynamometry, B-mode ultrasonography, electromyography, percutaneous muscle stimulation and magnetic resonance imaging were employed to acquire the parameters of interest.

Results: Following training, knee extensors peak isokinetic power increased by 28% ($P < 0.01$) in the flywheel group with no change in the weight-lifting group. Adaptations of the gastrocnemius muscle also occurred in both groups. The gastrocnemius characteristic with the highest response to training was tendon stiffness, with increases of 54% and 136% in the weight-lifting and flywheel groups, respectively ($P < 0.01$). The larger increase in tendon stiffness in the flywheel group was associated with an improvement in postural balance ($P < 0.01$).

Conclusion: Quadriceps flywheel loading not only produces a greater increase in power than weight training but its physiological benefits also transfer/overspill to the plantarflexor muscle–tendon unit resulting in a significantly improved balance. These findings support our initial hypotheses.

1. Introduction

Age-related losses in plantarflexor muscle and tendon functional properties are thought to contribute to the decline in postural balance in the elderly (Onambele et al., 2006). Previous studies have shown a link between the relatively sedentary status of a population and poor balance performance (Gauchard et al., 2003; Prioli et al., 2005), which suggests that this effect may be reversed through increased physical activity. Despite the documented benefits of exercise interventions on muscle and tendon mechanical properties (Morse et al., 2005; Reeves et al., 2005), positive effects on postural stability have mostly been shown in institutionalized older volunteers (Vanfraechem and Vanfraechem, 1977) and in diseased state in old age (Onambele and Degens, 2006), but rarely in independently living, healthy older adults.

It has been argued that any training regime that maximises muscle strength will ultimately improve functional abilities, including postural stance (Malbut-Shennan and Young, 1999). Indeed, not only has knee extensor muscle strength been shown to explain some of the variance in static balance (Carter et al., 2002; Lord et al., 2002; Sirola et al., 2004; Hess and Woollacott, 2005) but also, ankle plantarflexor muscle strength, activation capacity (AC) and tendon stiffness have been shown to explain the majority of the variance in static balance (Onambele et al., 2006).

Abbreviations: AP_d, anterior–posterior displacement; G-FWE, group trained using a flywheel inertial loading machine; G-Weight, group trained using a weight-resistance loading machine; ML_d, medio-lateral displacement; NME, neuromuscular function or neuromuscular efficiency; rEMG, relative EMG; T_d, total displacement

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However, strength-training studies often do not report an improved balance, whereas functional ability, such as walking speed, may improve (Wolfson et al., 1993; Schlicht et al., 2001; Gauchard et al., 2003).

It is also believed that strength-training regimes that incorporate a combination of concentric as well as eccentric modes of muscle loading would exhibit greater potential for improvement in muscle functional performance (Hruda et al., 2003). The rationale for this assumption is based on the postulation that an eccentric contraction would increment the absolute mechanical output (Linnamo et al., 2002), thereby creating a cycle of potentiated muscle mechanical responses. Indeed in a stretch-shortening cycle the concentric muscle action is somewhat enhanced by a preceding eccentric muscle action (Svantesson et al., 1994). Active muscles, when stretched, exert about 80–160% greater forces than during isometric contractions (Linari et al., 2000; De Ruiter and De Haan, 2001; Onambele, 2002; Onambele et al., 2004), because of a relative increase in the number of cross-bridges (Linari et al., 2000). Active muscle lengthening would thus be a more effective training stimulus for muscle strengthening. All in all, owing to the afore-mentioned link between strength and balance, a training regimen involving stretch-shortening cycles would be expected to result in relatively greater improvement in balance performance.

A form of training that may enhance the eccentric training stimulus is inertial loading since increased motor unit recruitment is required for breaking the flywheel inertia (Berg and Tesch, 1994; Pearson et al., 2001) during the return movement. Studies performed in young adults have previously shown the efficacy of isoinertial training in improving muscle mass (Seynnes et al., 2007) and limiting unloading-induced strength (isometric or dynamic) decrement (Tesch et al., 2004a, b). Whether this type of training would prove equally effective in older people and, because of the greater eccentric loading, also bring benefits in postural balance, is presently unknown. Thus, in order to maximise both isometric and dynamic contractile performances (hereafter referred to simply as 'strength') gains of the quadriceps muscle in response to training, in the present study we devised a program whereby participants would either be loaded in a conventional manner, or be trained with an isoinertial flywheel ergometer. Two hypotheses were put forward:

1. inertial training would be associated with greater quadriceps strength improvements compared with weight training and
2. the improvement in balance performance in the flywheel-trained participants would be over and above any balance improvements seen in the weight-trained group.

2. Materials and methods

2.1. Participants

Twenty-four healthy older participants (12 females) were randomly assigned to the group trained using a weight-resistance loading machine/G-Weight group (aged 70.2±1.5 years, body mass index 24.1±2.46 kg/m^2, $n = 12$ of whom $n = 6$ females) or the inertial flywheel-training group/G-FWE, (aged 69.6±1.1 years, body mass index 24.3±2.00 kg/m^2, $n = 12$). All participants gave written informed consent to take part in the study, which was approved by the University Board of Ethics.

2.2. Postural stability tests

The test of postural balance consisted of barefoot single-leg stance with both eyes-open. The hands were hanging freely, the knees were slightly apart and the knee of the non-supporting leg was bent at ~90° as described in detail by Onambele et al. 2006. A piezo-electric force platform (Kistler Inc., Basingstoke, Hants, UK) was used to obtain the three components of the ground reaction forces. Analogue data was acquired, and A/D converted at 100 Hz, using the BioWare 3.0 Export program (Kistler Inc., Basingstoke, Hants, UK). Measurements during the posturography tests included: trial duration (maximum 60 s), centre of pressure excursions, ground reaction forces, and electromyographic (EMG) activity of the medial head of the *vastus lateralis* (VL) and *gastrocnemius medialis* (GM) muscles. Trial duration was the period of time the participant managed to stay in the required stance. Centre of pressure excursion was quantified in terms of root mean square (RMS) as previously described: AP_d, ML_d, and T_d are the root square of the mean of centre of pressure excursions in anterior–posterior, medio-lateral, and a composite of the two directions, respectively (Baloh et al., 1998).

2.3. Maximal peak isokinetic knee extensors' function

To have an indication of the strength changes in the directly loaded muscle, maximal peak isokinetic power in knee extension (peak power) at an angular velocity of 180°/s, and unilateral isometric knee extension contractions (MVC) performed at a knee angle of 90°, were measured using a dynamometer (Cybex Norm, Phoenix Healthcare Products Ltd., UK), as previously described (Pearson and Onambele, 2005). Participants had previously visited the laboratory on at least one occasion and so were familiar with the procedures.

2.4. EMG recordings

The acquisition and processing of EMG signal were done following standard guidelines (Zipp, 1982a, b). Before EMG electrode placement, the skin was shaved and cleaned with an abrasive gel to reduce its impedance below 5000 Ω. EMG data were acquired at 2500 Hz, using surface bipolar Ag–AgCl electrodes 10 mm in diameter (Neuroline, Medicotest, Rugmarken, Denmark), set 20 mm apart along the muscle belly. Data were band-pass filtered between 50 and 500 Hz and then processed using a 40-ms running-window RMS.

The RMS–EMG of each muscle at the end of each trial (95–100% of trial duration) was divided by that at the beginning of the trial (0–5% of trial duration) as a measure of change in muscle activity during postural stance (Onambele et al., 2007). This ratio (rEMG) was taken as an index of neuromuscular efficiency or muscle fatigability.

Peak RMS–EMG (mV) in the quadriceps muscle was obtained over 1 s during the plateau phase of maximal knee extension contractions. The mean of 40 ms RMS–EMG running windows was taken as a measure of peak EMG activity during MVC.

2.5. Ankle plantarflexor muscle–tendon characteristics

Three ankle plantarflexor muscle–tendon characteristics were monitored since we have previously demonstrated a strong relationship between these parameters and postural stability (AP_d in particular (Onambele et al., 2006)):

I. Isometric plantarflexion MVC torque was recorded, while the participant was prone with the knees fully extended and the tested foot (left foot) strapped to the footplate of the isokinetic dynamometer described in the section above. To emulate the ankle joint angle during the postural tests, all MVC measurements were taken at 0° ankle angle (the foot at 90° with respect to the lower-leg axis).
II. To assess muscle AC during the plantarflexion MVCs, the twitch interpolation method was employed, as described in detail by Onambele et al. 2006. Supramaximal, square wave twitch doublets generated by an electro-stimulator (Alcatel Space, Switzerland SA) were applied to the triceps surae muscle through two surface electrodes on the calf. AC was calculated as $1-(IT/RT)\times 100$, where IT is the extra torque produced by a doublet superimposed on the MVC and RT is the torque produced by the doublet at rest.
III. Measurements of gastrocnemius tendon stiffness were taken by ultrasound during the plantarflexion MVCs, using the principles detailed elsewhere (Maganaris and Paul, 1999, 2002; Maganaris, 2002, 2005; Reeves et al., 2003). The gastrocnemius tendon forces corresponding to the above tendon elongations were estimated from the equation $F = cTQ \times MA^{-1}$, where cTQ is the plantarflexion torque corrected for both antagonistic (Magnusson et al., 2001) and synergistic (Fukunaga et al., 1992) muscle action about the ankle, and MA is the moment arm length of the Achilles tendon (Maganaris et al., 2001; Maganaris, 2004). Throughout, care was taken to control time-of-day at the pre- and post-training phases (Pearson and Onambele, 2005, 2006; Onambele-Pearson and Pearson, 2007).

2.6. Pilot experiment leading to a "transfer effect" hypothesis

The flywheel system in the current study was a prototype and so it was necessary to ascertain whether loading in the isoinertial and weight-training modes (see Fig. 1) would in fact elicit the same strategy of muscle contractions. Hence, a pilot study was conducted to quantify the degree to which the two modules would

Fig. 1. Main training loads. (A) *Variable inertial leg extensor called the Yo–Yo flywheel* (Berg and Tesch, 1998): The Rotary encoder allows the sensitive detection of the rotational properties of the flywheel from which the contractile velocity properties of the muscle can be inferred. The load cell (~9 kN maximum force reading capacity) is mounted in parallel with the loading belt to record forces. The loading discs (44 cm in diameter, available range of mass: 2.9–6.7 Kg) can be mounted either one at a time or in pairs to allow moment of inertia variations, thereby optimising the load for each participant. From the output of the rotary encoder and the load cell, muscle power is calculated as the product of force (*N*) and angular velocity (rad/s). (B) *Weight-training leg extensor.* (C) *Weight-training ankle rotator.*

differ/be similar in terms of the EMG activities each evoked. The VL, *vastus medialis* (VM) and GM muscles were simultaneously monitored in one session where the participants were allowed to use both loading modalities, with adequate rest periods between exertions. Angular displacement was simultaneously measured using a digital goniometer (Biometrics, Cwmfelinfach, Gwent, UK). Participants carried out two sets of 8 repetitions on each modality. To assess only those efforts where the participant was expected to be in the "full swing mode", the 2nd to the 7th contractions in each set of 8 were used for further analyses.

2.7. Training protocol

Training was progressive with the study population divided into those training with an inertial load (the G-FWE group) using the YOYO leg-extensor flywheel (Berg and Tesch, 1994; Tesch et al., 2004a, b) and those training on normal weight-resistance machines (Technogym, Gambettola, Italy), i.e. the G-Weight group, using a normal weight leg-extensor loading machine (Technogym, Gambettola, Italy). Knee extensions and flexions were performed at a comfortable speed on the Technogym equipment. On the YOYO, instructions were to contract as fast as possible during knee extension and to lightly resist the backward pull to the lever arm during knee flexion, thereby enabling complete return of the inertial wheel to its starting position without altogether stopping its movement. Both groups also used a weight-training ankle rotator (Technogym, Gambettola, Italy). Participants were familiarised with the exercises machines (See Fig. 1) for up to 2 weeks prior to the training regimen. The G-FWE group started training using the inertial load corresponding to maximal power output and this load was increased by 20% every other week. The G-Weight group was trained at 80% 1RM, and this value was also re-assessed every 2 weeks. In both groups, the number of contractions was sequentially incremented from 1 set of 8 repetitions at week one, to 4 sets of 12 repetitions at week 12. A recovery of ~5 min was introduced between sets. Compliance to training was very high, with only one drop-out and <5% of the sessions missed. Therefore, we formulated an additional hypothesis that, with the quadriceps strengthening effects of the leg extension exercises, any improvement in postural balance would be greater using the modality eliciting additional and highest 'overspill' muscular activity in the gastrocnemius, since this is a major player in postural balance maintenance (Loram et al., 2001; Loram and Lakie, 2002a, b; Onambele et al., 2006).

2.8. Statistics

The effects of training on postural balance and muscle–tendon parameters were statistically analysed by means of 2 (groups) × 2 (test times) two-way analyses of variance (ANOVA) models with the post-hoc Tukey test. Multiple linear regressions, using the stepwise forward procedure, were employed to assess whether the absolute values and/or relative changes in muscle–tendon characteristics could predict absolute and/or relative changes in balance indices. Durbin–Watson statistics was used to identify any correlation between the independent parameters and those with the highest variance inflation factor ($\geqslant$4.0), i.e. the collinear factors, were removed from the regression. For all statistical analyses, acceptance level was set at $P \leqslant 0.05$. Data are displayed as means ± S.E.M.

3. Results

3.1. EMG activity overspill

Total RMS–EMG activity for the duration of a contraction (hereafter only referred to as EMG activity), in the quadriceps during the concentric phase of leg extension was ~32% greater during the isoinertial contractions compared with the weight-training efforts. Conversely, EMG activity in quadriceps during the eccentric phase of leg extension was ~42% lower during the isoinertial contractions compared with the weight-training efforts. In the GM, EMG was 54% greater ($P<0.05$) in the concentric phase of loading, whilst using the flywheel inertial loading machine compared with exertions on the weight-training machine (Fig. 2). In the eccentric phase of loading, however, there was no difference in the EMG of the GM ($P>0.05$) between the two loading modes.

3.2. Baseline comparisons

The G-FWE and G-Weight groups showed no significant differences at baseline in quadriceps muscle strength and/or EMG activity (see Table 1). The two populations also showed no differences in any of the plantarflexors parameters of interest including muscle strength, AC or tendon stiffness (see Table 2), nor did they differ in balance performance indices including trial length, AP_d, ML_d, T_d, and rEMG (see Table 3).

3.3. Postural balance and training

Table 3 shows that after training, improvements in the G-FWE group were greater by 46% ($P<0.05$) than single-leg trial length increases in the G-Weight group. In this postural condition, the decrements in AP_d, ML_d, and T_d, in the G-FWE group were also more pronounced than in the G-Weight group. Table 3 also shows that there was a general trend for rEMG to be reduced after training. GM rEMG training-induced decrement was ~9% more pronounced in G-FWE compared with their G-Weight counterparts. Similarly, the training-induced decrement in VL rEMG was significantly more pronounced in the G-FWE group compared with their G-Weight counterparts.

3.4. Training-induced changes in knee extensors torque, peak power and NME

As detailed in Table 1, unilateral isokinetic quadriceps power only increased by 4% in the G-Weight group, whereas it increased by 28% in the G-FWE group. Unilateral isometric quadriceps strength only increased by 8% in the G-FWE group, whereas it increased by 17% in the G-Weight group. Interestingly, RMS–EMG decreased by 25% in the G-FWE group (denoting increased NME) whereas it increased by 27% in the G-Weight group, an indication of decreased NME.

3.5. Training-induced changes in gastrocnemius MVC, AC, and tendon stiffness

The results of the present study show a considerable improvement in plantarflexor muscle–tendon properties after both types of training in older individuals, with increments typically being largest in the G-FWE group (see Table 2).

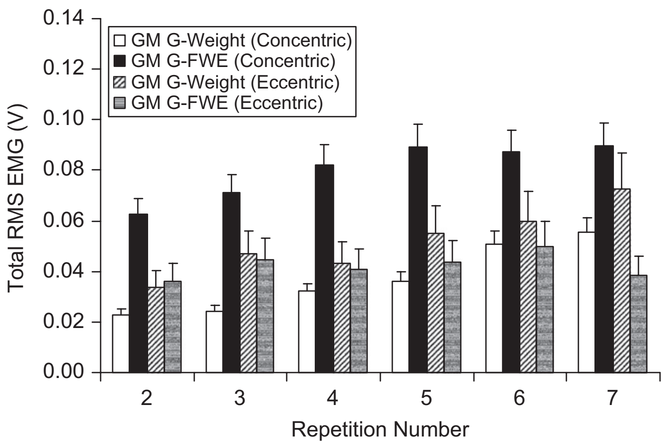

Fig. 2. Change in the EMG activity of the GM muscle during continuous concentric and eccentric (knee extension) contractions. Data are mean ± SEM.

3.6. Associations between training-induced changes in muscle parameters and balance performance

The multiple linear regressions performed showed that ~30% ($P<0.001$) of the variance in single-leg balance trial duration, and ~17% ($P<0.01$) of the variance in AP_d could be explained by a combination of plantarflexor MVC, AC, and tendon stiffness characteristics.

4. Discussion

In the present study, we hypothesised that compared with weight training, flywheel inertial loading of the knee extensors would result in greater improvements in indices of quadriceps strength and thus, in indices of postural balance (see below). Secondary hypotheses were that (a) loading of the knee extensors would have a "transfer" effect on the ankle plantarflexors and that this effect would be greater in isoinertial compared to weight training; (b) the higher degree of "transfer" in flywheel inertial

Table 1
Changes in the functional characteristics of the quadriceps with training

	G-FWE ($n=12$)			G-Weight ($n=12$)		
	Pre	Post	Change (%)	Pre	Post	Change (%)
Isometric knee extension MVC (Nm)	113 ± 13.5	122 ± 14.0	**8**	89 ± 11.2	116 ± 14.2	**17**
Dynamic knee extension power (W)	841 ± 125	1075 ± 161	**28**	843 ± 45	875 ± 39	**4***
RMS–EMG (mV)	1.22 ± 0.30	0.92 ± 0.26	**−25**	1.57 ± 0.18	1.99 ± 0.41	**27****

NB. Data are mean ± SEM. Comparisons of the % change in the isoinertial versus % change in the weight training groups, *$P<0.05$ and **$P<0.01$.

Table 2
Characteristics of the plantarflexors muscle–tendon unit during maximal isometric efforts

	G-FWE ($n=12$)			G-Weight ($n=12$)		
	Pre	Post	Change	Pre	Post	Change
Plantarflexion MVC (Nm)	56.7 ± 5.0	65.0 ± 6.7	**15%**	56.8 ± 7.0	57.2 ± 5.4	**0.7%**
Maximal plantarflexors force (N)	1415 ± 98	1719 ± 136	**22%**	1388 ± 137	1525 ± 103	**10%***
Antagonist Co-A in plantarflexion (%)	16 ± 3%	35 ± 6%	**19%**	14 ± 1%	38 ± 6%	**24%**
Plantarflexors activation capacity (%)	88 ± 6.2	95 ± 3.1	**7%**	87 ± 5.6	96 ± 1.4	**9%**
GM tendon stiffness (Nm m^{-1})	25 ± 1.6	59 ± 6.3	**136%**	26 ± 3.7	40 ± 6.9	**54%****
NME (Nm V^{-1})	0.9 ± 0.1	5.9 ± 0.9	~**5.5** ×	0.7 ± 0.1	3.9 ± 0.5	~**4.6** × **

NB. Data was acquired with the ankle at 90° angle. MVC is the maximal voluntary force. NME is neuromuscular efficiency (where maximal plantarflexion torque is divided by the average RMS–EMG of three plantarflexors muscles: GM, Gastrocnemius lateralis and soleus). Data are mean ± SEM. Comparisons of the % change in the isoinertial versus % change in the weight training groups, *$P<0.05$ and **$P<0.01$.

Table 3
Postural balance performance with training load

	G-FWE			G-Weight			Loading mode effect (G-weight versus G-FWE)(%)
	Pre	Post	Change (%)	Pre	Post	Change (%)	
Trial duration (s)	24.3 ± 5.2	35.2 ± 6.1	**45**	28.1 ± 7.7	27.9 ± 7.4	−**1***	|46|*
ML displacement (mm)	10.9 ± 1.5	8.9 ± 0.7	−**18**	10.5 ± 1.0	9.9 ± 1.4	−**6***	|12|
AP displacement (mm)	10.8 ± 1.1	9.1 ± 0.6	−**16**	12.3 ± 1.6	11.0 ± 1.0	−**11**	|5|
Total displacement (mm)	15.9 ± 1.6	13.0 ± 0.6	−**18**	16.3 ± 1.8	15.2 ± 1.6	−**7***	|11|
VL rEMG	1.7 ± 0.4	1.5 ± 0.3	−**12**	1.7 ± 0.4	1.6 ± 0.3	−**6**	**|6|***
GM rEMG	2.2 ± 0.9	1.7 ± 0.4	−**23**	1.4 ± 0.3	1.2 ± 0.2	−**14**	**|9|***

Please note that the symbol | | denotes absolute values, *Denotes $P<0.05$ when comparing the difference in changes within and/or between groups.

loading would explain the greater improvements in balances associated with this type of loading.

Our data show that a combination of strength training is significantly beneficial to the postural control of otherwise healthy independent-living older adults. We have also shown that, flywheel inertial loading is particularly effective for training the knee extensors in older people, as it optimises dynamic (though not isometric) strength and balance improvements compared with conventional knee-extensors weight training. Our findings have therefore partly confirmed our hypotheses.

4.1. *Effect of training mode on indices of balance performance*

It is notable that both training groups showed significant improvements in trial duration, with the inertial group exhibiting 46% greater increments. It is also noteworthy that the direction of changes in sway amplitude did not always follow the incremented trial durations seen with training. In this context, our results are similar to previous findings (Crilly et al., 1989; Torvinen et al., 2002) in that training regimes that improve muscle strength and balance duration do not necessarily decrease sway amplitude. In fact, apart from a few exceptions such as the example of a dorsiflexion electrostimulation training study (Amiridis et al., 2005), centre of pressure displacement *per se* is a very difficult parameter to improve. Our results showed that the main difference in the magnitude of sway improvement was in the medio-lateral direction. This is in itself not surprising since the main muscles trained with the different loading devices were those acting on the upper leg, and hence those affecting medio-lateral sway.

The present findings of training-induced decrements in rEMG activity during the balance trials (Amiridis et al., 2005) and changes in the ratio of EMG to unit torque during the maximal voluntary contractions (Seynnes et al., 2007), are in agreement with previous findings. These results are suggestive of increased NME and/or increased fatigue resistance in the trained population. Again here, the G-FWE group showed greater benefits compared to their G-Weight counterparts. Similarly, the findings of improved muscle AC with training support the view that increasing postural sway in the elderly represents deterioration, at least in part, in the nervous system and may therefore improve with interventions involving increased motor unit recruitment.

4.2. *The link between altered muscle–tendon properties and improved balance*

The muscle group targeted in the two differential loading modes responded as expected in terms of strength increment. Indeed the loading mode that involved the highest quadriceps EMG activity was the same mode that showed the greatest increase in quadriceps peak power: this was flywheel inertial loading. In addition, the latter was also the loading modality exhibiting the greatest "loading transfer" to the plantarflexors. We also found that, in terms of reversing the effects of ageing, the G-FWE group fared best in terms of improvements in plantarflexors muscle strength, AC, and tendon stiffness. This is an important finding since the three muscle–tendon properties have previously (Onambele et al., 2006) been associated with postural stability. The mechanism of the transfer of benefits to the plantarflexors whilst loading the knee extensors is however unclear. Nevertheless, it remains that the greatest "transfer" of quadriceps loading to the leg muscles in both training groups was on the gastrocnemius tendon. This tendon also exhibited the largest overspill (i.e. greater increased tendon stiffness) in the G-FWE. The above findings would indicate that the difference in balance improvement was due to the greater adaptation of the tendon in the G-FWE group. How would loading of the quadriceps transfer to the plantarflexors muscles? One possible mechanism may be that generalised lower-limb tension during the knee extension contractions was associated with plantarflexor muscle recruitment. The significant EMG activity of the GM during knee extensions, supports this proposition. This would occur since focal muscle action causes activation of synergistic muscles in various body regions that are in the direct plane of the original movement. This concept is referred to as "movement shadow"(Rondot, 1991).

4.3. *Differences between the two training modalities*

As mentioned earlier, there was a discrepancy in the instructions given to participants in terms of speed of contraction, and this may have caused some of the observed differences in muscle responses. It is therefore possible that the EMG results may be explained by examination of the loading and velocity components of the two movements. Indeed, other studies have suggested that the rapid contractions characteristic of inertial loading can partly explain the sizeable increments in strength with this type of loading (Valour et al., 2004).

An additional confounding factor may have been linked to our observation that with flywheel inertial loading the highest EMG activities occurred at the knee angles corresponding to longer fascicle lengths ($\sim$90–100°), whereas with weight training the highest EMG activities were seen at the knee angles corresponding to shorter fascicle lengths ($\sim$170–180°). It is possible that training-induced muscle strength increment depends on the length of the contractile component during the application of loading. Moreover, it is possible that the overly extended joint when the load was highest during weight training simply put the quadriceps at a mechanical disadvantage (van Eijden et al., 1987), hence diminishing both the contractile forces that could be produced and the stimulus to increase muscle strength.

5. Conclusions

The present study has shown that flywheel inertial loading of the main locomotor muscles (knee extensors) results in greater improvements in muscle peak power and balance than weight training. The latter appears to be mediated through an overspill of loading to the plantarflexor muscles and tendons.

Conflict of interest

The authors have no conflict of interest to report.

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