Mastergradsoppgave

Bilateral deficit during maximum voluntary isometric and dynamic muscle contractions at different loads.

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Contents

Bilateral svekkelse ved maksimale frivillige isometriske og dynamiske muskelkontraksjoner ved ulike motstander.

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Sammendrag

Intensjonen med dette studiet var å undersøke fenomenet bilateral svekkelse (BLD) av kraft og power på ulike motstander ved å sammenligne kneekstensjon ved monolaterale (ML) og bilaterale (BL) muskelkontraksjoner. Forskjeller i variablene kraft, effekt og hastighet mellom ML og BL bevegelser, ble brukt for å evaluere en eventuell BLD. Seks godt trente idrettsstudenter deltok i denne studien. Hver enkelt deltaker gjennomførte dynamiske bevegelser ved 20, 40, 60 og 80 % av egen kroppsvekt (BW), samt isometrisk muskelkontraksjoner i både ML og BL bevegelser. Alle deltakerne gjennomførte de samme eksperimentelle prosedyrene og alle kondisjoner var randomisert. BLD ble ikke observert ved isometriske muskelkontraksjoner. I kontrast, de dynamiske bevegelsene viste i gjennomsnitt en BLD målt som peak kraft (5.63% ± 1.53, $P = 0.01$). I sammenligning med de respektive belastningene, viste det en signifikant BLD kun på 20 % (6.96%, $P = 0.03$) og 80 % (7.41%, $P = 0.01$) av kroppsvekt. Resultatene for peak power viste ikke en BLD, men i stedet en bilateral fasilitering (BLF). Gjennomsnittlig BLF var 7.27 % ± 3.5 ($P = 0.007$). Det ble også observert en signifikant høyere peak hastighet ved BL muskelkontraksjoner med en gjennomsnittlig forskjell på 8.82 % ($P = 0.005$) mellom BL og MLl (venstre side), og 11.31 % ($P = 0.0001$) mellom BL og MLr (høyre side). Konklusjonen er at BLD eksisterer ved kneekstensjon ved måling av peak kraft, uavhengig av ulike motstander. Ved måling av peak power og peak hastighet, blir en BLF observert. Resultatene fra denne studien kan indikere at BLD og BLF eksisterer i ulik grad, og det tyder på at det er forskjeller mellom isometriske og dynamiske bevegelsesoppgaver.

Nøkkelord: bilateral svekkelse, kneekstensjon, singelledd, effekt

Bilateral deficit during maximum voluntary isometric and dynamic muscle contractions at different loads.

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Abstract

The intention of the present study was to explore the phenomenon bilateral deficit (BLD) of force and power at different loads by comparing a knee extension exercise in monolateral (ML) and bilateral (BL) muscle contractions. Differences in the variables force, power and velocity between ML and BL movements were used to evaluate a possible BLD. Six well-trained sport science students participated in the study. Each subject conducted dynamic muscle contraction at 20, 40, 60 and 80 % of their own body weight (BW), and isometric muscle contractions in both ML and BL movements. All participants did the same experimental procedures in a randomized order. BLD was not observed in the isometric muscle contractions. In contrast, the dynamic muscle contractions showed in average a BLD measured as peak force measurements (5.63% ± 1.53, P = 0.01). In comparison of the respective loads, there were only significant BLD observed at 20 % (6.96%, P = 0.03) and 80 % (7.41%, P = 0.01) of BW. The results for peak power did not show a BLD, but in contrast a bilateral facilitation (BLF). The average BLF was 7.27 % ± 3.5 (P = 0.007). There was also observed a significant higher peak velocity in BL muscle contractions with an average difference of 8.82 % (P = 0.005) between BL and MLl (left limb), and 11.31 % (P = 0.0001) between BL and MLr (right limb). In conclusion, BLD exist in knee extension exercise when measuring peak force, independent of different loads. When measuring peak power and peak velocity, a BLF is observed. The results of this study may indicate that BLD and BLF exist in various degrees, and that there are differences between isometric and dynamic movement tasks.

Key words: bilateral deficit, knee extension, single joint, power

Introduction:

The human neuromuscular system is capable of performing motor tasks of great complexity, but several studies report an inability of human subjects to generate maximum force when bilateral muscle pairs operate simultaneously (Jakobi & Cafarelli, 1998). This has been known since Asmussen and Heebøll-Nielsen (1961) found that the maximum voluntary force, during bilateral (BL) isometric muscle contractions in an attempted leg extension, was lower than the sum of the monolateral (ML) muscle contraction forces. This phenomenon is reported in studies of different muscle groups, in old, young and adolescent females, in athletic and non athletic subjects, and in different movement patterns (Bobbert, Graaf, Jonk & Casius, 2006; Howard & Enoka, 1991; Kuruganti & Murphy, 2008; Kuruganti & Seaman, 2006; Rejc, Lazzer, Antonutto, Isola & di Prampero, 2010).
The sum of two ML muscle contraction forces, minus the BL muscle contraction force, divided by the sum of the two ML forces is defined bilateral deficit (BLD).

($\mathrm{BLD} = \frac{\mathrm{MLr+MLl-BL}}{\mathrm{MLr+MLl}}$), where r and l indicate right and left limb (Rejc et al. 2010).

BLD is generally associated with differences in neuromuscular control between ML and BL muscle contractions. Determining whether differences exist between one- and two-limb movements may provide insight into complex neuromuscular control patterns (Jakobi & Chilibeck, 2001).

No clear explanation has emerged in the literature which explains the BLD phenomenon (Jakobi & Cafarelli, 1998). But some possible theories have been suggested, and according to Ohtsuki (1983), BLD is most likely to come from either interhemispheric inhibition or division of attention. Howard and Enoka (1991) did not find any force deficits during simultaneous contractions of muscles anatomically distant from each other, but they found a BLD in symmetrical muscles, and argued strongly against the influence of division of attention. They also concluded that BLD may be due to a neural inhibition during symmetrical BL muscle contractions (Howard & Enoka, 1991).

Hay, de Souza and Fukushiro (2006) studied ML and BL multi-joint leg press where the external load was relatively equal for ML and BL efforts. Electromyography (EMG) BLD was found in every muscle except in m. rectus femoris in one study. BLD ranged from 6.1 % to 20.9 %. They concluded that BLD exists, but that individual muscle activation levels and joint kinetics are not equally affected. They also suggested that differences in muscle coordination in ML versus BL play a role in determining BLD. Bobbert et al. (2006) analyzed the difference between one-leg and two-leg squat jumps, carried out with the same load (body weight), to investigate the possible contribution of non neural factors to the BLD in jumping. They found that the mechanical work of the right leg was more than 20 % less in the two-leg jump than in the one-leg jump, and that the shortening velocities in the two-leg jump were higher than in the one-leg jump. They claimed that 75 % of the BLD could be explained by the difference in contraction conditions of muscles, because the muscles traveled their range of shortening at greater speed in the two-leg jump than in the one-leg jump. And because of the force- velocity relationship, they therefore produced less force. Only the remaining 25 % could therefore be attributed to a reduction of neural drive. They concluded that the BLD in jumping is primarily caused by the force-velocity relationship rather than by a reduction of neural drive.

This hypothesis assumes that the force-velocity relationship is the same in ML and BL conditions, and that BLD is due mainly to a shift along the force velocity-relationship, which comes by the smaller load per limb in BL compared to ML muscle contractions (Rejc et al. 2010).

Rejc et al. (2010) investigated the force-velocity relationship during BL versus ML explosive lower limb contractions, performed with different loads. They concluded that BLD seemed to be due to a reduction of neural drive and to a different muscular coordination. The inter-muscular coordination seemed to be different between BL and ML contractions, but BLD did not seem to be due to changes of the force-velocity relationship. However, this study was done on a multi-joint movement, which is a more complex movement task compared to a single joint movement, and may demand more muscular coordination in order to perform well.

During explosive efforts, the coordination of the active muscles plays a crucial role in overall performance, and would give an explanation why BLD exists (Hay et al., 2006, Rejc et al., 2010).

On the other hand, some studies have also shown a bilateral facilitation (BLF) when comparing ML and BL muscle contractions, and especially in subjects participating in activities requiring simultaneous activation of homologues muscles, such as weightlifting and rowing (Häkkinen, Kraemer & Newton, (1997), Howard & Enoka, (1991), Schantz, Moritani, Karlson, Johansson & Lundh, 1989).

Häkkinen et al. (1997) found BLF when testing BL and ML isometric and concentric muscle contractions of the knee extensor in men and women of different ages. They suggested, based on their findings, that in a single-joint exercise and especially at explosive strength of the knee extensor, the contraction-force decreases by increasing age. They claimed that this was due to selective muscle atrophy and/or to a decrease in the rate of voluntary activation of the muscles.

Howard and Enoka (1991) tried to determine whether BLD was due to neural factors, by testing untrained subjects, cyclists and weightlifters on isometric muscle contractions. The untrained subjects showed a BLD, but the cyclist did not, and the weightlifters showed a BLF. In the second experiment the untrained subjects and the weightlifters performed maximum left leg extensions while the right leg rested or was activated by electric stimulation. This experiment showed an increase in the voluntary maximal force in the left leg during right leg electromyostimulation. This increase of force was greatest in the BLF subjects, which indicates that interlimb interactions during BL muscle contractions are mediated by neural mechanisms.

It is also reported an increased electromyographic activity in the contralateral limb in cases of ML training, which only can be explained by a cross educational effect by neural factors (Åstrand, Rodahl, Dahl & Strømme, 2003).

Schantz et al. (1989) tried to find out if BLD could be due to an inability to fully activate a large number of muscles simultaneously. They found a 10 % BLD in leg extension exercises, but a 4 % BLF was discovered when comparing ML and BL knee extensions. They argued that the knee extensor muscles were not the cause of the lower leg extension force.

Most studies that have investigated the BLD phenomenon have tested on isometric muscle contractions, and those who showed a BLD on dynamic muscle contraction movements have been testing in multi-joint exercises. The new aspect in the present study was to explore eventually differences in BLD for maximum voluntary contraction (MVC) in isometric and dynamic muscle contractions at different loads in a single-joint exercise. The aim of this study was to: (a) determine if BLD exists in a single-joint isometric and dynamic MVC, and (b) to find out if there are different degrees of BLD at different loads. The hypothesis was that BLD exists in a single-joint exercise, and in a similar degree, independent of different loads.

Methods

Subjects

Six well-trained sport science students, 4 males and 2 females, from North Troendelag University College volunteered to participate in the study and the baseline characteristics of the subjects are given in table 1. The experiment was carried out in the middle of the school semester in the spring. The participants had experience with various sport activities, but none had been active with sports that primarily require contraction of homologues muscles simultaneously. All subjects had experience with general resistance training in the last year, and all participants gave their written informed consent to participate in the study. The ethical aspect of the study was obtained following the principals outlined in the declaration of Helsinki.

Table 1: Baseline characteristics (mean ± SD) of subjects

Age (year):	22.3 ± 2.7
Stature (m):	1.76 ± 0.06
Body mass (kg):	76.9 ± 7.4
BMI (kg/m^2):	24.9 ± 2.2

BMI: body mass index

Experimental design

After a brief familiarization session with the laboratory equipment and experimental task, the subjects performed two tests in the same experimental session: (1) maximum voluntary, isometric contraction, and (2) maximum voluntary, dynamic contractions at different loads (% of body weight (BW)) of the knee extensor muscles. The apparatus used was loaded knee extension apparatus with weight blocks (see figure 1). All participants (N= 6) did the same experimental procedures in a randomized order. Starting position was with the knee joint in 90°, and with the body laying down on the bench with a strap over the hip, to keep the hip steady in all trials. This was done to isolate the movement. The superior side of the subject's ankle was pressing against the pads of the machine (illustrated in figure 1). In the ML muscle contractions, the resting limb was resting at 90° without any movement. The participants were told that the focus of the test was to implement maximum execution speed and to provide maximum force.

After a standardized general and specific warm-up procedure, they conducted each condition once, and each graph was saved for further analysis. They tested dynamic muscle contractions at 20 %, 40 %, 60 % and 80 % of their own BW, and on isometric muscle contractions. There was in total 15 experimental conditions and all conditions were randomized for BL and ML limbs (MLl-left limb and MLr-right limb). The different loads used in ML muscle contractions of each limb were halved compared to the BL muscle contractions, so in total, it would be equal load between ML and BL muscle contractions. To prevent fatigue, the subjects rested for 2 minutes after each contraction, but stayed passive (seated or laying down on the knee extension machine) during the recovery time.

Figure 1: View of the exercise equipment which was used in the experiment.

Measurement of power, force and velocity

The dependent variables peak power (P=F*v), peak force (N=m*a), peak velocity (m/s) and time to peak velocity were measured with a force transducer load cell (model 333A) in combination with linear encoder, both connected to Muscle Lab Model 4010/4020e (Ergotest Technology A.S) The identification of the dependent variables is illustrated in figure 2. To calculate the different loadings for each subject, BW of each participant was used as basis.

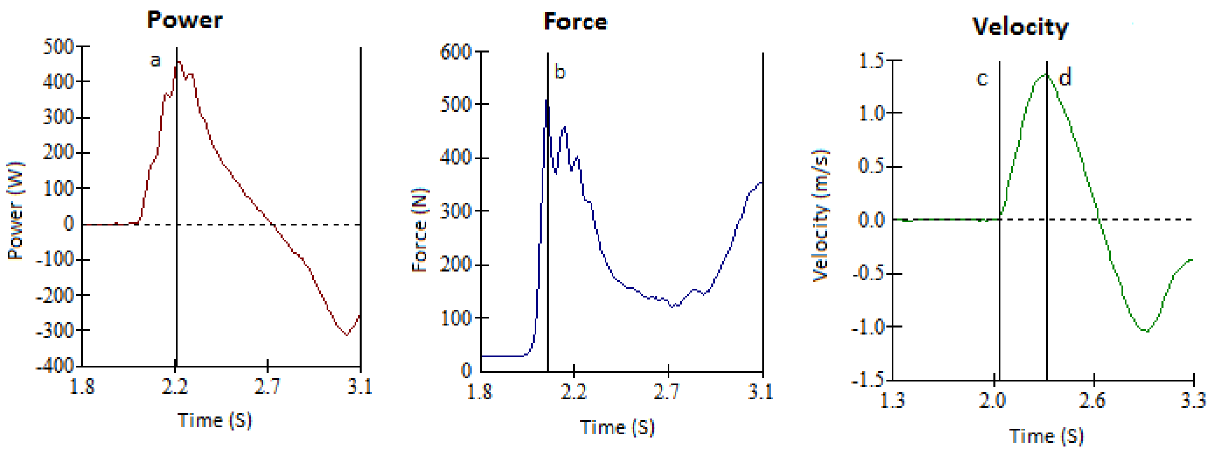

Figure 2: Determination of peak power (a), peak force (b) and peak velocity (d) in the knee extension exercise. The difference between (c) and (d) gives the time to peak velocity.

Statistical analysis

Statistical analysis was carried out with SPSS (Statistical Package Social Sciences, SPSS INC., Chicago, IL). Results are presented as mean ± standard deviation (SD) unless otherwise stated. Conventional methods were used for the calculation of means and SD. Paired samples t-test was used to discover changes between the different percentages of efforts in ML and BL muscle contractions. Data were checked for normality by use of the Shapiro-Wilks test. Statistical significance was accepted at the 5 % level ($P < 0.05$).

Results:

Bilateral deficit – peak force

There was a significant BLD in dynamic muscle contractions at 20 % ($P = 0.03$) and 80 % ($P = 0.01$) of BW in peak force measurements. No differences was discovered between ML and BL isometric muscle contractions ($P = 0.59$). There was no significant BLD in dynamic muscle contractions in 40 % ($P = 0.19$) and in 60 % ($P = 0.30$) of BW. There was a significant BLD overall in the force measurements in dynamic contractions of 5.63 % ± 1.53 ($P = 0.01$) (figure 3).

Bilateral deficit – peak power

There was no significant BLD in either of the different loads in peak power measurements. The tendency for peak power measurements indicates that BL muscle contractions are bigger than ML muscle contractions with an average BLF of 7.27 % ± 3.5 ($P = 0.007$) (figure 4).

Table 2: Difference of the dependent variables in ML and BL muscle contractions (n = 6; mean ± SD)

Variables:	Total (n= 6) Monolateral:	Bilateral:	Difference(%)***
Isometric PF	1294.43 ± 298.18	1317.86 ± 278.17	-1.88 %
Dynamic 20 % PF	579.53 ± 112.74	541.78 ± 112.13*	6.96 %
Dynamic 40 % PF	749.3 ± 91.39	706.78 ± 96.44	6.01 %
Dynamic 60 % PF	869.13 ± 126.68	838.9 ± 115.91	3.60 %
Dynamic 80 % PF	981.8 ± 149.83	914.01 ± 127.27*	7.41 %
Dynamic 20 % PP	733.11 ± 194.02	832.96 ± 232.54**	-11,98 %
Dynamic 40 % PP	808.81 ± 223.11	837.58 ± 178.29	-3,43 %
Dynamic 60 % PP	809.4 ± 249.53	871.16 ± 199.34	-7,08 %
Dynamic 80 % PP	742.55 ± 242.14	795.25 ± 218.91	-6,62 %

* = Indicates a significantly BLD.
**= Indicates a significantly BLF.
***= Positive value indicates BLD, and negative value indicates BLF.
(PF=Peak force, PP=Peak power)

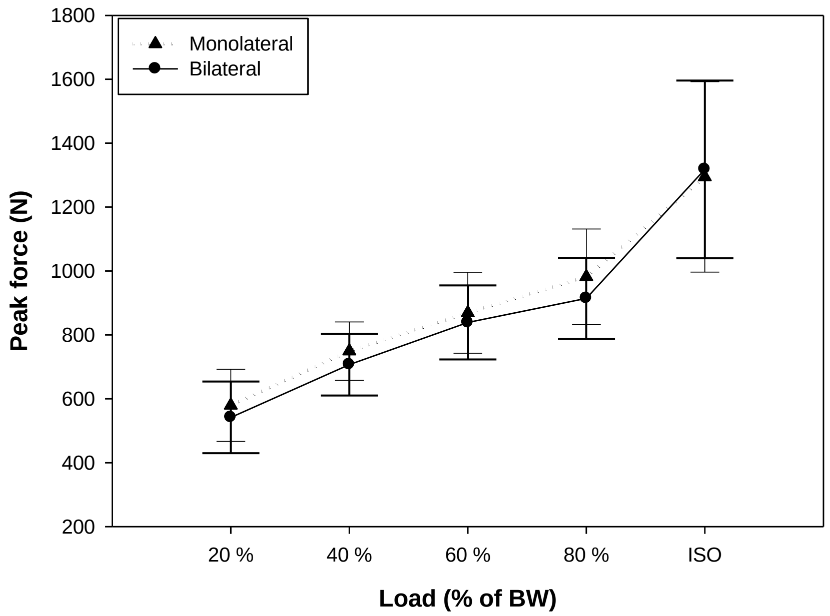

Figure 3: Comparisons of changes in peak force at different loads in both ML and BL muscle contractions. Measured in Newton (N) and the values are means ± SD (n = 6).

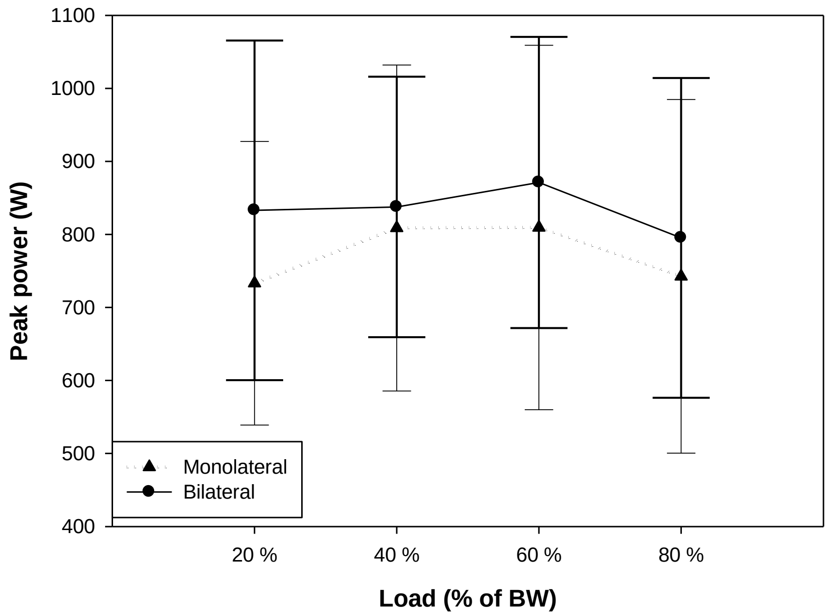

Figure 4: Comparisons of changes in peak power at different loads in both ML and BL muscle contractions. Measured in watts (W) and the values are means ± SD (n = 6).

Peak velocity

The average peak velocities were significantly different between BL (1.76 ± 0.57 m/s) and MLl (1.61 ± 0.51 m/s) muscle contractions, with a difference of 8.82 % (P = 0.005). A significant difference was also observed when comparing average peak velocity of BL (1.76 ± 0.57 m/s) and MLr (1.56 ± 0.56 m/s) muscle contractions, with a difference of 11.31 % (P = 0,0001) (figure 6). Time to peak velocity (TPV) was similar between BL (0.29 ± 0.06) and MLl (0.29 ± 0.08), but it was significantly higher at MLr (0.33 ± 0.08) versus BL muscle contractions (P = 0.0002) (figure 5).

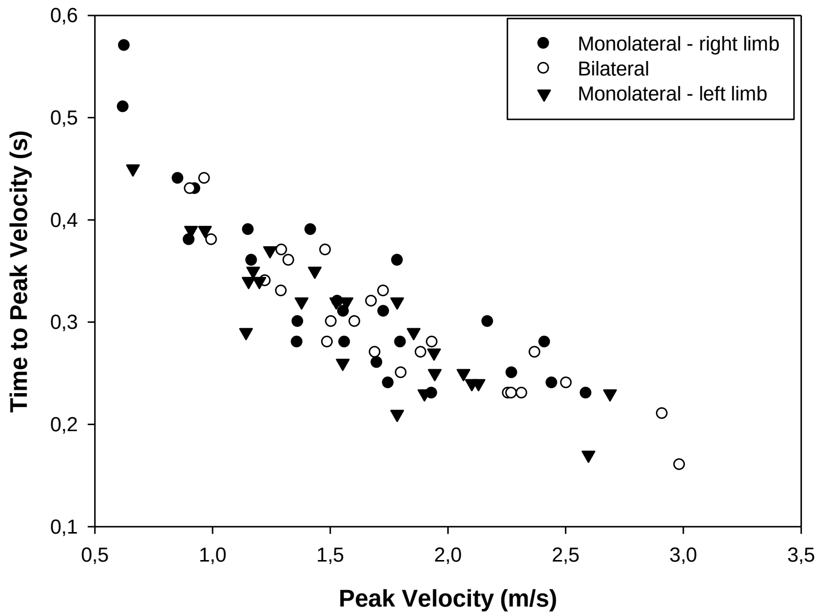

Figure 5: Comparisons of peak velocity (m/s) and time to peak velocity (s) in all trials.

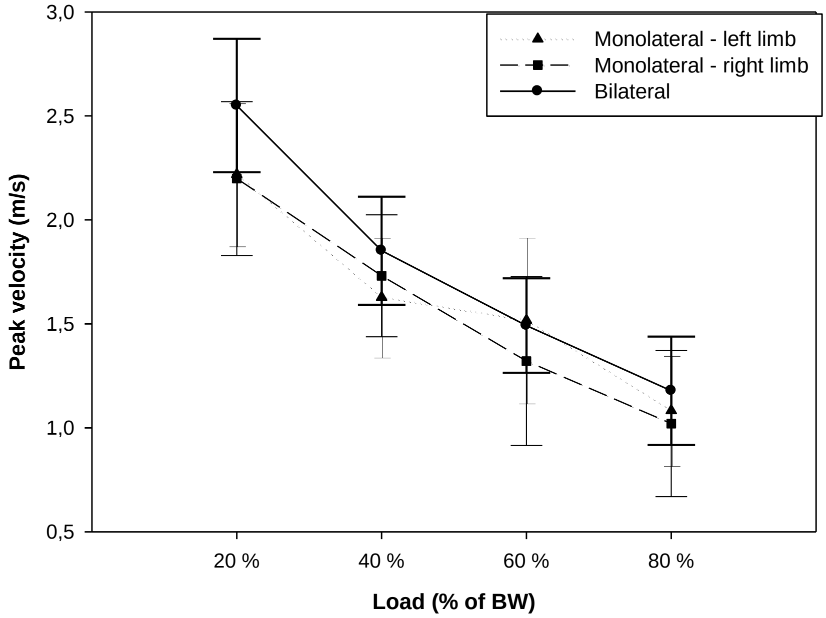

Figure 6: Comparisons of changes in peak velocity at different loads in ML left limb (MLl), ML right limb (MLr) and BL muscle contractions. Measured in velocity (m/s) and the values are means ± SD (n = 6).

Discussion

In this study the BLD in a knee extension exercise at different loads, was examined. The main finding of this study was that it was observed differences between dynamic and isometric muscle contractions. No difference was observed between ML and BL in isometric muscle contractions. In contrast, BLD was significant in dynamic muscle contractions in peak force measurements, and a significant BLF was observed in dynamic muscle contractions in peak power measurements. The degree of differences between BL and ML muscle contractions was approximately equal on the different loads. This indicates that BLD exist in a single-joint exercise during dynamic movements, and that the relationship between BL and ML muscle contractions is unaffected of different loads.

Differences in peak force

The hypothesis was that BLD exists in a single-joint exercise, and that it is the same degree of BLD, independent of different loads. The result of the present study showed no BLD in isometric muscle contractions. This result complements the result of Howard and Enoka (1991), who did not find BLD in an isometric knee extension exercise on cyclists, but only on untrained subjects. Although the subjects in the present study were well-trained, they were not a homologues group, since they were participating in different sport activities. And it is possible that training status of the participants may affect the degree of BLD. It is also reported that weightlifters and rowers have replaced the BLD by a BLF when conducting isometric muscle contractions. This shows that there may be an enhancing effect due to neural factors when BL homologues muscles are contracted, which may explain the BLF effect (Åstrand et al. 2003).

Even though it was not observed BLD in isometric muscle contractions, there was a significant BLD in the dynamic muscle contractions. However, this BLD was small compared to other studies (Bobbert et al., 2006, Hay et al., 2006, Rejc et al., 2010). It seems that the degree of BLD is approximately equal, which indicates that BLD is a steady phenomenon that is not affected by different loads. Rejc et al. (2010) found an approximately equal degree of BLD, during dynamic muscle contractions on different loads in a leg extension exercise. In their opinion, the occurrence of BLD was due to a reduction of neural drive and different muscular coordination.

Differences in peak power

In the peak power measurements there was observed a BLF. The results showed a significant reduction of peak power in ML muscle contractions compared to BL muscle contractions. The peak power results showed an average BLF of 7.27 % ± 3.5, which indicates that the degree of BLF is unaffected and more or less equal in the different loads. Since a BLF is observed in the dynamic movements, it is possible that BLF in the power measurements is due to a higher increase of velocity compared to a decrease in force when BL muscles are contracted simultaneously. Based on these findings and on the results by Howard and Enoka (1991), it seems that the ability to exhibit a BLD or a BLF depends on factors that influence the integration of neural signals from peripheral and central sources. This shows that the BLD and BLF can be influenced by afferent feedback, and that it can be affected by exercise.

Differences in peak velocity

Peak velocity in the present study shows a big difference between BL and ML muscle contractions, and a significant higher peak velocity in BL compared to ML. TPV was significantly lower in BL- versus MLl- muscle contractions, and similar between BL- and MLr- muscle contractions. This indicates that when conducting BL muscle contractions, the acceleration of the movement is faster in BL- versus ML- muscle contractions. This complements the differences between the results in peak power and peak force measurements.

Conclusion

Most studies that have been mentioned in the introduction have reported a BLD when comparing contractions of BL and ML muscles in homologues muscles, and mainly in isometric muscle contractions. The results from Schantz et al. (1989) showed a BLD in the multi-joint exercise and a BLF in the single-joint exercise. Several other studies have also reported a BLF in single-joint exercises (Häkkinen et al., 1997, Howard & Enoka, 1991, Jakobi & Cafarelli, 1998). These findings also complement the findings in the present study where it was observed a BLF in the power measurements in a single-joint exercise. Based on the studies that were mentioned above, and of the findings in the present study, it seems that there are differences between single-joint and multi-joint exercises. This can be due to different muscle groups which is being investigated, and to different training background of the participants (Hay et al., 2006, Rejc et al, 2010, Taniguchi, 1998). Häkkinen et al. (1997) found no BLD in a single-joint isometric and maximal 1RM concentric exercise, and concluded that the activation and force production of the BL muscle groups were sustained during BL muscle contractions. This may indicate that BLD occurs in a greater extent when performing complex movement tasks, which can come from different muscular coordination and a limited ability for neuromuscular control. It is also possible that BLD occurs as a result of different force/velocity relationship, since the muscles traveled their range of shortening at greater speed in the BL muscle contractions compared to the ML muscle contractions. And because of the force-velocity relationship, they therefore produced less force (Howard & Enoka, 1991, Rejc et al., 2010).

In light of the results in the present study, and in the other studies which have been mentioned in the introduction, it is likely to believe that the degree of BLD and BLF are dependent of numerous factors. It seems that the exercise as it is being conducted is important in relation to the degree of BLD, in terms of single-joint versus multi-joint exercises. Training status, and activities which the subjects are participating in, may also affect the degree of BLD and BLF. A conclusion of this investigation is that BLD is present in a single-joint, knee extension exercise, during dynamic muscle contractions when measuring peak force, but not when measuring peak power. The degree of BLD on different loads seems to be about equal.

Limitations

The task which the subjects were given during the MVC was to perform maximal effort. There is no guarantee that the subjects managed to perform a maximal effort on each attempt, which can affect the result to a greater extent. It would also be of interest to perform the same study with two force transducer load cells, to see if the force-velocity relationship changes when conducting BL and ML muscle contractions. Based on the findings in the present study, it is difficult to state the exact reason why BLD and BLF appear in different degrees, and further research is needed to detect which factors that are affecting BLD and BLF.

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References:

Asmussen, E., and Heebøll-Nielsen, K. (1961). Isometric muscle strength of adult men and women. *Comm Danish Nat Ass for Infant Paral.* 11:3-43.

Bobbert, M.F., de Graaf W.W., Jonk, J.N., and Casius, L.J. (2006). Explanation of the bilateral deficit in human vertical squat jumping. *Journal of Applied Physiology.* 100:493-499.

Hay, D., de Souza, V.A., and Fukashiro, S. (2006). Human bilateral deficit during a dynamic multi-joint leg press movement. *Human Movement Science.* 25:181.191.

Häkkinen, K., Kraemer, W.J. and Newton, R.U. (1997). Muscle activation and force production during bilateral and unilateral concentric and isometric contractions of the knee extensor in men and women at different ages. *Electromyogr. Clin. Neurophysiol.* 37: 131-142.

Howard, J.D., and Enoka, R.M. (1991). Maximum bilateral contractions are modified by neutrally mediated interlimb effects. *Journal of Applied Physiology.* 70:306-316.

Jakobi, J.M., and Cafarelli, E. (1998). Neuromuscular drive and force production are not altered during bilateral contractions. *Journal of Applied Physiology.* 84(1):200-206.

Jakobi, J.M., and Chilibeck, P.D. (2001). Bilateral and unilateral contractions: Possible differences in maximal voluntary force. *Canadien Journal of Applied Physiology.* 26(1):12-33.

Kuruganti, U., and Murphy, T. (2008). Bilateral deficit expressions and myoelectric signal activity during submaximal and maximal isometric knee extensions in young, athletic males. *European Journal of Applied Physiology.* 102:721-726.

Kuruganti, U., and Seaman, K. (2006). The bilateral leg strength deficit is present in old, young and adolescent females during isokinetic knee extension and flexion. *European Journal of Applied Physiology.* 97:322-326.

Ohtsuki, T. (1983). Decrease in human voluntary isometric arm strength induced by simultaneous bilateral exertion. *Behavioural Brain Research.* 7:165-178.

Rejc, E., Lazzer, S., Guglielmo, A., Isola, M., and di Prampero, P.E. (2010). Bilateral deficit and EMG activity during explosive lower limb contractions against different overloads. *European Journal of Applied Physiology*. 108:157-165.

Schantz, P.G., Moritani, T., Karlson, E., Johansson, E., and Lundh, A. (1989). Maximal voluntary force of bilateral and unilateral leg extension. *Acta Physiol. Scand*. 136: 185-192.

Taniguchi, Y. (1998). Relationship between the modifications of bilateral deficit in upper and lower limbs by resistance training in humans. *European Journal of Applied Physiology*. 78:226-230.

Åstrand P.O., Rodahl K., Dahl H.A., and Strømme S.B. (2003). *Textbook of work physiology*. 4th ed, Human Kinetics. 649 p.