

Bampouras, Theodoros ORCID: <https://orcid.org/0000-0002-8991-4655> , Reeves, Neil D., Baltzopoulos, Vasilios and Maganaris, Constantinos N. (2017) Interplay between body stabilisation and quadriceps muscle activation capacity. *Journal of Electromyography and Kinesiology*, 34 . pp. 44-49.

Downloaded from: <http://insight.cumbria.ac.uk/id/eprint/2783/>

Usage of any items from the University of Cumbria's institutional repository 'Insight' must conform to the following fair usage guidelines.

Any item and its associated metadata held in the University of Cumbria's institutional repository Insight (unless stated otherwise on the metadata record) may be copied, displayed or performed, and stored in line with the JISC fair dealing guidelines (available [here](#)) for educational and not-for-profit activities

provided that

- the authors, title and full bibliographic details of the item are cited clearly when any part of the work is referred to verbally or in the written form
 - a hyperlink/URL to the original Insight record of that item is included in any citations of the work
- the content is not changed in any way
- all files required for usage of the item are kept together with the main item file.

You may not

- sell any part of an item
- refer to any part of an item without citation
- amend any item or contextualise it in a way that will impugn the creator's reputation
- remove or alter the copyright statement on an item.

The full policy can be found [here](#).

Alternatively contact the University of Cumbria Repository Editor by emailing insight@cumbria.ac.uk.

**Please note that the full version of this paper appears in the Journal of
Electromyography and Kinesiology -**

[http://www.jelectromyographykinesiology.com/article/S1050-6411\(17\)30109-8/abstract](http://www.jelectromyographykinesiology.com/article/S1050-6411(17)30109-8/abstract)

Title

Interplay between body stabilisation and quadriceps muscle activation capacity

Authors

Theodoros M. Bampouras^{1,2}, Neil D. Reeves², Vasilios Baltzopoulos³, Constantinos N. Maganaris⁴

Affiliations

¹ Department of Medical and Sport Sciences, University of Cumbria, Lancaster, UK

² School of Healthcare Science, Manchester Metropolitan University, Manchester, UK

³ Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge, UK

⁴ Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK

Keywords: electromyography, interpolated twitch technique, isometric knee extension, maximum voluntary contraction, quadriceps torque

Corresponding author:

Theodoros M. Bampouras, Department of Medical and Sport Sciences, University of Cumbria, Lancaster LA1 3JD, UK / +44 1524 590837 /

Theodoros.bampouras@cumbria.ac.uk /

Abstract

The study aimed to distinguish between the effect of stabilisation and muscle activation on quadriceps maximal isometric voluntary contraction (MVC) torque generation. Nine subjects performed a) an MVC with restrained leg and pelvis (Typical MVC), b) a Typical MVC with maximal handgrip (Handgrip MVC), c) an MVC with only the leg contracting (Leg MVC), and d) an MVC with unrestrained leg and pelvis (Unrestrained MVC). Quadriceps torque and activation capacity differences between conditions were compared with repeated measures ANOVA and dependent t-tests, while EMG (from eleven remote muscles) was compared using Friedman's and Wilcoxon. Typical MVC (277.2 ± 49.6 Nm) and Handgrip MVC (261.0 ± 55.4 Nm) were higher than Leg MVC (210.2 ± 48.3 Nm, $p < 0.05$) and Unrestrained MVC (195.2 ± 49.7 Nm, $p < 0.05$) torque. Typical MVC ($83.1 \pm 15.9\%$) activation was higher than Leg MVC ($68.9 \pm 24.3\%$, $p < 0.05$), and both Typical MVC and Handgrip MVC ($81.8 \pm 17.4\%$) were higher than Unrestrained MVC ($64.9 \pm 16.2\%$, $p < 0.05$). Only flexor carpi radialis, biceps brachii, triceps brachii and external oblique muscles showed EMG differences, with Leg MVC consistently lower than Typical MVC or Handgrip MVC. Stabilisation of the involved segments is the prime concern subsequently allowing fuller activation of the muscle, reinforcing the need for close attention to stabilisation during dynamometry-based knee joint functional assessment.

Introduction

Isometric torque produced by maximal voluntary contraction (MVC) of the quadriceps is routinely used to assess knee joint function by dynamometry in various populations, such as clinical (e.g. [Hart et al, 1984; Souza et al, 2009]) or aged (e.g. [Reeves et al, 2004; Thompson et al, 2013]), as well as to assess the impact of various interventions (e.g [Labrunée et al, 2012; Stock and Thompson, 2014]). The results of this assessment depend on the muscle size of the subject, as well as their ability to voluntarily activate the knee extensor muscles tested [Bampouras et al, 2006; Kent-Braun and Le Blanc, 1996]. In addition, they can be affected by the subject's stabilisation on the dynamometer seat [Hart et al, 1984; Magnusson et al, 1993].

With regards to body stabilisation, it has been shown that when hands were used to hold onto the dynamometer and the back was fixed to it, higher knee extensors torque by 6.4 % was generated compared to when only the back was fixed, which, in turn, generated higher torque by 7.5% than when no stabilisation at all was used [Magnusson et al, 1993]. On the other hand, it has been shown that stabilising the subject and, in particular, their pelvis on the dynamometer seat, allows for greater fixation of the rectus femoris origin [Hart et al, 1984]. This facilitates activation and hence greater force production by the rectus femoris muscle, contributing to increased quadriceps torque, as the rectus femoris accounts for ~17% of quadriceps torque [McNair et al, 1991].

The activation of the tested agonist muscle, however, can potentially be enhanced through a different path. During an isometric quadriceps MVC, it is common for subjects to simultaneously contract a number of other muscles, remote to the tested muscle, to achieve maximum torque [Jacobsen et al, 2012]. The activation of those remote muscles may augment the tested muscle's activation capacity, and subsequent torque produced, through a phenomenon termed concurrent activation potentiation (CAP) [Ebben, 2006; Ebben et al,

2008]. CAP is underpinned by the theory of motor overflow, which suggests that when a motor area is active, other areas are affected by that activation [Hoy et al, 2004]. In the primary motor cortex, which controls movements of the face, arms, and legs [Donohue and Sanes, 1994], activation of one area would also result in higher activation of the others. Indeed, this theory has been supported by studies reporting that contraction of remote muscles to the tested quadriceps, e.g. jaw and arms, results in higher knee extensor torque [Ebben et al, 2008].

Stabilisation and muscle activation are strongly interlinked, as a more stable segment will allow for higher muscle activation and, consequently, muscle force and torque generation. During quadriceps muscle strength assessment, if the pelvis is not adequately stabilised, the bicep femoris muscle is likely to become more active to contribute more substantially towards ensuring stabilisation of the pelvis [van Wingerden et al, 2004]. In turn, this will reduce the force generated by the quadriceps muscle, through increased reciprocal neural inhibition by the hamstrings contracting to stabilise the pelvis [Hamm and Alexander, 2010], as well as the increased antagonistic torque. Similarly, remote voluntary contractions can augment the agonistic muscle's torque by increasing stabilisation (for example, hands gripping onto the dynamometer, [Magnusson et al, 1993]; the Valsalva manoeuvre increasing intra-thoracic pressure through activation of various torso muscles, stabilising the core, [Harman et al, 1998]) or by directly increasing agonistic muscle activation capacity.

Being able to distinguish between stabilisation and activation effects on torque generation could help avoiding erroneous conclusions and difficulty in comparisons between studies of muscle function assessment. Therefore, the aim of the present study was to determine the effect of stabilisation and muscle activation capacity on the quadriceps maximum voluntary isometric torque, by manipulating subject stabilisation configurations on a dynamometer seat and inclusion of simultaneous remote voluntary contractions.

Methods

Subjects

Following Institutional ethics approval, nine healthy, active males (mean \pm SD: age 28.7 ± 6.8 years, stature 1.78 ± 0.08 m, body mass 89.3 ± 13.0 kg) free from any musculoskeletal injuries gave written, informed consent to participate in the study. In order to reduce variability in performance, all subjects were familiarised with the experimental procedures (4) and visited the laboratory on a single occasion for testing.

Isometric knee extension strength measurement

Each subject's isometric knee extension strength was initially determined by performing two maximum voluntary contractions (MVC). For those MVCs, the subjects were sat in the chair of a custom-made dynamometer (1) with the hip, knee and ankle joint angles at 90° . The lever arm and the bed of the dynamometer was very rigid, while the restraints allowed for better fixation of the pelvis and the subjects' body compared to commercially available dynamometers. Straps were positioned over the pelvis and tested right thigh, to prevent extraneous movement, while the tested right leg was securely strapped, above the lateral malleolus, to a force-transducer (KAP, E/200 Hz, Bienfait B.V. Haarlem, The Netherlands). If the coefficient of variation (calculated as standard deviation / average * 100) between the two MVCs was $<5\%$, the two MVCs were averaged, otherwise a third MVC was performed and the closest two were averaged (average MVC). Handgrip strength was assessed with the use of a dynamometer (Takei Scientific Inst. Co. Ltd, Niigata, Japan) and the same procedure as for the MVC was followed.

Subsequently, subjects performed an MVC under four different conditions, in a randomised, counterbalanced order. During all four MVCs, the subjects had their arms crossed over their chest and adequate rest between trials was provided. The conditions were:

a) an MVC as described above (Typical MVC),

- b) an MVC as the Typical MVC but with the addition of exerting maximal handgrip force (Handgrip MVC),
- c) an MVC where the subjects were instructed to isolate the contraction to their leg muscles only (Leg MVC) with the rest of the muscles relaxed, and
- d) an MVC where there were no restraining straps on the pelvis and tested thigh (Unrestrained MVC). During all MVCs, subjects were asked to exert as much force as possible against the ankle strap.

Force signals were corrected for passive tension of the knee extensors and real-time force readings were displayed online and recorded (Matlab, The Mathworks, Natick, MA). The perpendicular distance from the centre of the knee joint to the point where force was applied (at the level of the ankle, at right angles to the longitudinal axis of the lower leg) was measured and multiplied by that force to provide torque, which was used for further analysis.

Muscle activation capacity measurement

Two 7 x 12.5-cm self-adhesive carbon rubber electrodes (Versa-Stim, ConMed, New York, USA) were placed on the proximal and distal regions of the quadriceps muscle group. Stimuli of 200- μ s pulse width and 10-ms inter-stimulus gap were generated by an electrical stimulator (model DS7, Digitimer stimulator, Welwyn, Garden City, UK). Electrical stimuli application was displayed online along with the force signal.

Doublets were applied at rest and at increments of 50mA, with the voltage set at 300 V. The intensity that resulted in generating one third of the average MVC torque [Bampouras et al, 2012] was recorded and used for the experiment. Subsequently, a doublet was applied at the plateau phase of each MVC (superimposed) and 4 seconds after the superimposed twitch and while the subject was relaxed (resting). Muscle activation capacity was quantified from the superimposed and resting twitch torque using the interpolated twitch technique according to the equation $((1 - (\text{superimposed twitch torque} / \text{resting twitch torque})) * 100)$.

Electromyography (EMG) measurement

Two surface Ag-AgCl electrodes of 10mm diameter each were placed in a bipolar configuration on flexor carpi radialis, biceps brachii, triceps brachii (long head), deltoid, pectoralis major, sternocleidomastoid, rectus abdominis, external oblique, vastus lateralis, biceps femoris (long head), and latissimus dorsi muscles to obtain EMG signals. The placement area was prepared by shaving and alcohol cleansing and all electrodes were placed perpendicular to the muscle fibres, with a centre-to-centre distance of 20mm and on the right handside, except for the vastus lateralis where the contralateral muscle was used. These muscles were selected as the more likely muscles to contract during the MVCs described above and, thus, provide an indication of muscle activity during contractions as well as adherence to instructions for the Leg MVC.

EMG was collected at a sampling rate of 2000Hz, and filtered with a high- and low-pass filter of 10 and 500Hz, respectively. The signal was subsequently smoothed using root mean square over 30ms (Aqknowledge, Biopac Systems, Santa Barbara, California) and a mean value from a 500ms window was taken during the plateau phase of the MVC and prior to the application of the twitch. As no comparison between subjects or muscles was to be conducted and testing took place in a single session, no EMG normalisation was performed.

Statistical analysis

Normality of distribution of the data was checked using Shapiro-Wilk test and subsequently confirmed for handgrip strength, torque and muscle activation capacity but not for EMG.

Consequently, a repeated measures ANOVA was used to compare torque and muscle activation capacity between all four MVC conditions, followed by dependent t-test for pairwise comparisons when differences were found. In addition, a dependent t-test was used to compare handgrip strength at baseline and during Handgrip MVC. Friedman's test was used to compare EMG between conditions for all muscles followed by Wilcoxon test where

differences were found. Holm-Bonferroni adjustment was used for all pairwise comparisons and the adjusted p values are presented for these comparisons.

Effect sizes (ES) were calculated for significantly different comparisons to provide an indication of the magnitude of the effect, with 0.8, 0.5 and 0.2 representing large, moderate and small effects for parametric tests effects sizes and 0.5, 0.3 and 0.1 representing large, moderate and small effects for non-parametric tests effects sizes [Fritz et al, 2012]. For all statistical analysis IBM SPSS Statistics v 22 was used. Data are presented as means \pm SD, unless otherwise stated. Statistical significance level was set at $p < 0.05$.

Results

Average MVC torque from the two initial MVCs was 298.1 ± 56.7 Nm while submaximal stimulation intensity was 372 ± 123.0 mA.

A significant overall difference was found for torque between the four conditions ($p = 0.001$). Subsequent analysis revealed that Typical MVC was significantly higher than Leg MVC ($p = 0.008$, ES = 1.4) and Unrestrained MVC ($p = 0.004$, ES = 1.7), while Handgrip MVC was also significantly higher than Leg MVC ($p = 0.034$, ES = 1.0) and Unrestrained MVC ($p = 0.008$, ES = 1.3) (Figure 1). In addition, handgrip strength was not significantly different ($p = 0.282$) between handgrip performed on its own (44.4 ± 6.4 kg) and Handgrip MVC (41.6 ± 6.1 kg).

FIGURE 1 ABOUT HERE

Muscle activation capacity was significantly different between conditions ($p = 0.001$), with higher activation for Typical MVC compared to Leg MVC ($p = 0.020$, ES = 0.7) and Unrestrained MVC ($p = 0.002$, ES = 1.1), and higher activation for Handgrip MVC compared to Unrestrained MVC ($p = 0.001$, ES = 1.0) (Figure 2). No other differences for activation were found.

FIGURE 2 ABOUT HERE

EMG differences between conditions ($p < 0.05$) were seen for the flexor carpi radialis, biceps brachii, triceps brachii (long head) and external oblique muscles (Figure 3) only. For the flexor carpi radialis, Leg MVC was lower than Typical MVC ($p = 0.036$, ES = 0.9), Handgrip MVC ($p = 0.036$, ES = 0.8) and Unrestrained MVC ($p = 0.036$, ES = 0.8). For the biceps

brachii, Leg MVC was lower than Handgrip MVC ($p = 0.036$, $ES = 0.8$) and Unrestrained MVC ($p = 0.036$, $ES = 0.8$). For the triceps brachii (long head), Leg MVC was lower than Typical MVC ($p = 0.012$, $ES = 0.9$). Finally, for the external oblique muscle, both Leg MVC ($p = 0.036$, $ES = 0.8$) and Unrestrained MVC ($p = 0.036$, $ES = 0.8$) were lower than Handgrip MVC.

FIGURE 3 ABOUT HERE

Discussion

The aim of the study was to examine the effect of subject stabilisation and muscle activation capacity on knee joint torque developed during an isometric MVC, by distinguishing the effect of each component through manipulation of stabilisation configurations and inclusion of remote voluntary contractions. The results suggest that although both stabilisation and activation capacity play an important role in force generation, stabilisation of the involved segments plays the major role which will in turn allow fuller activation of the muscle.

When the handgrip was added to the Typical MVC, no statistically significant change in torque or muscle activation was observed. Our results agree with CAP literature showing that when bilateral handgrip was added to knee extension, torque from an isometric contraction [Ebben et al, 2009] or dynamic contraction [Cherry et al, 2010] did not change, suggesting no beneficial effect of handgrip on knee extensor torque. Similarly to the present study, handgrip strength was also not significantly reduced during the knee extension (Cherry et al, 2010; Ebben et al, 2008). These findings contradict expectations of increased activation and subsequent torque due to increased H-reflex activity and motor-evoked potentials induced by the additional handgrip contraction (Dowman and Wolpaw, 1988; Péréon et al, 1995).

One possible reason for this contradiction is the contraction of the handgrip-related muscles not being sufficient to excite further the difficult to activate (possibly due to its higher content of type II muscle fibres; [Johnson et al, 1973]) quadriceps muscle [Behm et al, 2002], as suggested by the very similar activation values during Typical MVC and Handgrip MVC. A second possible reason relates to the action performed with the handgrip. When the arms were used to grab the dynamometer seat, ensuring a better-fixed torso, an increase in knee extension torque was seen [Magnusson et al, 1993]. However, the handgrip contraction used in the present study and Ebben et al [2008] and Cherry et al [2010] studies, does not appear to substantially contribute towards stabilising the torso. Therefore, although excitatory

responses may take place during the grip, these do not assist in further stabilising the pelvis during knee extension. This notion is supported by findings that gripping the dynamometer seat or the pelvic strap during knee extension had no effect on quadriceps torque [Kramer, 1990], most likely due to the fact that both actions offered the same stabilising effect to the torso.

When the subjects were requested to focus on contracting the leg muscles only (Leg MVC) while still restrained by the dynamometer belt, activation was reduced by 17.5%, while torque was reduced by 24.2% when compared to the Typical MVC values. EMG data suggests that subjects were able to 'engage less' the flexor carpi radialis, biceps brachii, triceps brachii (long head) and external oblique muscles, as the EMG values were lower during the Leg MVC. In a study examining the EMG activity of muscles used in our study (biceps femoris (long head), external oblique, rectus abdominis) during an isotonic exercise, however, those muscles were shown to have lower activation during the isotonic exercise [Jacobsen et al, 2012]. If this is the case in the present study, then it is unlikely that the reduction in quadriceps activation values was due to the reduced EMG activity of those muscles. Interestingly, the rest of the EMG data showed no difference between any of the conditions. This could mean that other muscles were not required for the contraction, and hence, they remained 'quiet' throughout all conditions, or they were crucial to the contraction and therefore they were activated to achieve the task required, regardless of the instruction. Whichever the reason, the lack of difference in EMG activity between conditions for the rest of the muscles studied, precludes them as contributors to the muscle activation capacity changes.

When the pelvis and tested right thigh restraints were removed (Unrestrained MVC), the reduction in activation (22.0%) and torque (29.6%) compared to typical MVC, was higher than the respective reduction in activation and torque seen in Leg MVC condition, although

not statistically significantly so. Given that the subjects' EMG in the measured muscles during Unrestrained MVC was equal or higher than the corresponding EMG values during Leg MVC, it is reasonable to assume that CAP did not augment knee extensor torque, as otherwise activation and torque would be higher in the Unrestrained condition. Collectively, these findings suggest that pelvis and tested thigh stabilisation is the major factor determining the knee extensor torque produced during an isometric knee extension, and optimal stabilisation subsequently facilitates muscle activation enabling maximum possible force generation by the tested muscles.

The subjects in the present study were familiar with maximal isometric contraction, as per Typical MVC. However, the Leg MVC condition inevitably contained two potentially conflicting instructions ('push as hard as possible against the ankle strap' and 'use only your leg muscles, relax the other ones'). This could have presented a limitation to the force generation during this condition as the opposing instruction requirement could impact negatively on maximum force generation [Marchant, 2010]. In addition, during the Unrestrained MVC, there was a tendency for subjects to lift off the dynamometer seat. However, they all maintained a position similar to the Typical MVC. It is likely that this position was maintained by voluntary activation reduction to prevent further lifting off the chair, which supports further the concept of the need for stabilisation first to enable maximum voluntary activation of the muscles.

In conclusion, the present findings suggest that although stabilisation and activation are interlinked, stabilisation of the pelvis during an isometric knee extension is a priority in order to allow maximum voluntary activation of the quadriceps muscle. These results further reinforce the need for close attention to stabilisation during dynamometry-based knee joint functional assessment.

References

- Bampouras TM, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. Is maximum stimulation intensity required in the assessment of muscle activation capacity? *J Electromyogr Kinesiol.* 2012;22(6):873-7.
- Bampouras TM, Reeves ND, Baltzopoulos V, Maganaris CN. Muscle activation assessment: effects of method, stimulus number, and joint angle. *Muscle Nerve.* 2006; 34(6):740-46.
- Behm DG, Whittle J, Button D, Power K. Intermuscle differences in activation. *Muscle Nerve.* 2002;25(2):236-43.
- Button DC, Behm DG. The effect of stimulus anticipation on the interpolated twitch technique. *J Sports Sci Med.* 2008;7(4):520-4.
- Cherry E, Brown L, Coburn J, Noffal G. Effect of remote voluntary contractions on knee extensor torque and rate of velocity development. *J Strength Cond Res.* 2010;24(9):2564-9.
- Donohue JP, Sanes JN. Motor areas of the cerebral cortex. *J Clin Neurophysiol.* 1994;11(4):382-96.
- Dowman R, Wolpaw JR. Jendrassik maneuver facilitates soleus H-reflex without change in average soleus motoneuron pool membrane potential. *Exp Neurol.* 1988;101(2):288-302.
- Ebben WP. A brief review of concurrent activation potentiation: theoretical and practical constructs. *J Strength Cond Res.* 2006;20(4):985-91.
- Ebben WP, Leigh DH, Geiser CF. The effect of remote voluntary contractions on knee extensor torque. *Med Sci Sports Exerc.* 2008;40(10):1805-9.
- Fritz CO, Morris PE, Richler JJ. Effect size estimates: current use, calculations, and interpretation. *J Exp Psychol.* 2012;141(1): 2-18.
- Hamm K, Alexander CM. Challenging presumptions: Is reciprocal inhibition truly reciprocal? A study of reciprocal inhibition between knee extensors and flexors in humans. *Man Therap.* 2010;15(4):388-93.

Harman EA, Frykman PN, Clagett ER, Kraemer WJ. Intra-abdominal and intra-thoracic pressures during lifting and jumping. *Med Sci Sports Exerc.* 1988;20(2):195-201.

Hart DL, Stobbe TJ, Till CW, Plummer RW. Effect of trunk stabilization on quadriceps femoris muscle torque. *Phys Ther.* 1984;64(9):1375-80.

Hoy KE, Fitzgerald PB, Bradshaw JL, Armatas CA, Georgiou-Karistianis N. Investigating the cortical origins of motor overflow. *Brain Res Rev.* 2004;46(3):315-27.

Jakobsen MD, Sundstrup E, Andersen CH, Bandholm T, Thorborg K, Zebis MK, Andersen LL. Muscle activity during knee-extension strengthening exercise performed with elastic tubing and isotonic resistance. *Int J Sports Phys Ther.* 2012;7(6):606-16.

Johnson MA, Polgar J, Weightman D, Appleton D. Data on the distribution of fibre types in thirty-six human muscles. An autopsy study. *J Neurol Sci.* 1973;18(1):111-29.

Kent-Braun JA, Le Blanc R. Quantitation of central activation failure during maximal voluntary contractions in humans. *Muscle Nerve.* 1996;19(7):861-9.

Kramer JF. Effect of hand position on knee extension and knee flexion torques of intercollegiate rowers. *J Orthop Sports Phys Ther.* 1990;11(8):367-71.

Labrunée M, Antoine D, Vergès B, Robin I, Casillas J, Gremeaux V. Effects of a home-based rehabilitation program in obese type 2 diabetics. *Ann Phys Rehab Med.* 2012;55(6):415-29.

Magnusson SP, Geismar RA, Gleim GW, Nicholas JA. The effect of stabilization on isokinetic knee extension and flexion torque production. *J Athl Train.* 1993;28(3):221-5.

Marchant DC. Attentional focusing instructions and force production. *Front Psychol.* 2010;1:210.

McNair PJ, Marshall RN, Matheson JA. Quadriceps strength deficit associated with rectus femoris rupture: a case report. *Clin Biomech.* 1991;6(3):190-2.

Péréon Y, Genet R, Guihéneuc P. Facilitation of motor evoked potentials: timing of Jendrassik maneuver effects. *Muscle Nerve.* 1995;18(12):1427-32.

Reeves ND, Narici MV, Maganaris CN. In vivo human muscle structure and function: adaptations to resistance training in old age. *Exp Physiol*. 2004;89(6): 675-89.

Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther*. 2009;39(1):12-9.

Stock MS, Thompson BJ. Effects of barbell deadlift training on submaximal motor unit firing rates for the vastus lateralis and rectus femoris. *PLoS One*, 2014;9(12):e115567.

Thompson BJ, Ryan ED, Sobolewski EJ, Conchola EC, Cramer JT. Age related differences in maximal and rapid torque characteristics of the leg extensors and flexors in young, middle-aged and old men. *Exp Gerontol*, 2013;48(2): 277-82.

van Wingerden J, Vleeming A, Buyruk H, Raissadat K. Stabilization of the sacroiliac joint in vivo: verification of muscular contribution to force closure of the pelvis. *Eur Spine J*. 2004;13(3):199-205.

Figure captions

Figure 1. Isometric knee extension torque in all four different conditions (Typical MVC, subjects sat in the dynamometer chair with straps over the pelvis and tested right thigh; Handgrip MVC, as the Typical MVC but with the addition of exerting maximal handgrip force; Leg MVC, subjects were instructed to contract their leg muscles only with the rest of the muscles relaxed; Unrestrained MVC, no restraining straps on the pelvis and tested thigh). Values are means and SD. Significant differences with Typical MVC are indicated by an asterisk, while significant differences with Handgrip MVC are indicated by a dagger symbol.

Figure 2. Quadriceps activation capacity in all four different conditions (Typical MVC, subjects sat in the dynamometer chair with straps over the pelvis and tested right thigh; Handgrip MVC, as the Typical MVC but with the addition of exerting maximal handgrip force; Leg MVC, subjects were instructed to contract their leg muscles only with the rest of the muscles relaxed; Unrestrained MVC, no restraining straps on the pelvis and tested thigh). Values are means and SD. Significant differences with Typical MVC are indicated by an asterisk, while significant differences with Handgrip MVC are indicated by a dagger symbol.

Figure 3. Mean quadriceps EMG in all four different conditions (Typical MVC, subjects sat in the dynamometer chair with straps over the pelvis and tested right thigh; Handgrip MVC, as the Typical MVC but with the addition of exerting maximal handgrip force; Leg MVC, subjects were instructed to contract their leg muscles only with the rest of the muscles relaxed; Unrestrained MVC, no restraining straps on the pelvis and tested thigh) for flexor carpi radialis (Panel A), biceps brachii (Panel B), triceps brachii (long head) (Panel C) and external oblique muscles (Panel D). Values are means and SD. Significant differences are

indicated by a, difference with Typical MVC; b, difference with Handgrip MVC; c, difference with Leg MVC; d, difference with Unrestrained MVC.









