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**Insight into the function of the obturator internus muscle in
humans: Observations with development and validation of
an electromyography recording technique**

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Abstract

There are no direct recordings of obturator internus muscle activity in humans because of difficult access for electromyography (EMG) electrodes. Functions attributed to this muscle are based on speculation and include hip external rotation/abduction, and a role in stabilization as an “adjustable ligament” of the hip. Here we present (1) a technique to insert intramuscular EMG electrodes into obturator internus plus (2) the results of an investigation of obturator internus activity relative to that of nearby hip muscles during voluntary hip efforts in two hip positions and a weight-bearing task. Fine-wire electrodes were inserted with ultrasound guidance into obturator internus, gluteus maximus, piriformis and quadratus femoris in ten participants. Participants performed ramped and maximal isometric hip efforts (open kinetic chain) into flexion/extension, abduction/adduction, and internal/external rotation, and hip rotation to end range in standing. Analysis of the relationship between activity of the obturator internus and the other hip muscles provided evidence of limited contamination of the recordings with crosstalk. Obturator internus EMG amplitude was greatest during hip extension, then external rotation then abduction, with minimal to no activation in other directions. Obturator internus EMG was more commonly the first muscle active during abduction and external rotation than other muscles. This study describes a viable and valid technique to record obturator internus EMG and provides the first evidence of its activation during simple functions. The observation of specificity of activation to certain force directions questions the hypothesis of a general role in hip stabilisation regardless of force direction.

Keywords Obturator internus, electromyography, ultrasound guidance, hip stability, hip external rotation

Introduction

Amongst leg muscles, few have been subject of as much speculation regarding their function as the deep lateral hip rotator muscles. This is particularly true for the obturator internus muscle, which, has been attributed functions as diverse as hip external rotation and abduction [Gray, 1989], hip stabilisation (regardless of direction of force) [O'Rahilly, 1986; Hall-Craggs, 1990], and provision of a stable attachment for the levator ani muscles [DeLancey, 1994]. Anatomists have even attributed opposite actions [Basmajian et al., 1989]. No recordings of electromyography (EMG) have been reported in humans.

Obturator internus is considered inaccessible for EMG recordings [Gray, 1989]. Surface EMG is not appropriate for deep muscles and intramuscular electrode placement is difficult because of its small size and proximity to neurovascular structures [Stern et al., 1993]. Placement of intramuscular electrodes is particularly challenging as much of the obturator internus bulk lies inside the pelvis. Consequently, even the simplest predictions regarding this muscle's function remain untested.

Obturator internus arises from the internal surface of the obturator membrane and the obturator foramen, then passes through the lesser sciatic foramen, underneath the sacrotuberous ligament, to the exterior of the pelvis and the lateral aspect of the greater trochanter of the femur [Gray, 1989]. Based on predictions from anatomy [Gray, 1989] and EMG studies in apes [Stern et al., 1993], most texts define obturator internus as a hip external rotator and abductor, although adduction has also been proposed [Basmajian et al., 1989]. The orientation of the deep hip lateral rotator muscles in parallel with the femoral neck is interpreted to suggest a role in hip stabilisation [O'Rahilly, 1986; Hall-Craggs, 1990] to hold the femoral head in the

acetabulum [Morris, 1953; Moore, 1985]. Extensive levator ani muscle attachment to fascia overlying obturator internus implies a contribution to support of continence mechanisms [DeLancey, 1994; Hulme et al., 1999]. Clarification of the role(s) of the obturator internus muscle requires EMG recordings of obturator internus activity.

Here we describe a novel technique to insert intramuscular EMG electrodes into obturator internus in humans. We also aimed to validate the source of muscle activity recorded with the electrodes through comparison to the activity of surrounding muscles, and to investigate activity of the obturator internus in a range of maximal hip efforts in two hip positions, as its function may vary with hip angle [Dostal et al., 1986; Delp et al., 1999], and during simple functions.

Materials and Methods

A method for insertion of intramuscular EMG electrodes into obturator internus

Anatomical considerations: Muscle fibres of obturator internus arise as a broad fan-like structure inside the pelvic cavity and narrow to a tendinous region as they pass externally to attach to the greater trochanter. The tendon is flanked by the inferior and superior gemelli and is covered by gluteus maximus. The gemelli originate from the external aspect of the ischium and attach to the obturator internus tendon [Shinohara, 1995]. The region of the muscle accessible to recordings with less potential for crosstalk is that within the pelvis, away from the gemelli. A technique was developed using ultrasound imaging to guide placement based on observation of cadavers.

Insertion technique: With the participant in prone the ischial tuberosity and sacrotuberous ligament are palpated and marked on the skin. Obturator internus is visualised with the ultrasound transducer placed along the sacrotuberous ligament

(line between ischial tuberosity and sacrum [Fig. 1]) and the vascular structures are identified in cross-section (located medially and highlighted with colour Doppler ultrasound). The muscle abuts the ischial tuberosity as a triangular region with boundaries that move during hip external rotation. At this point the transducer is then rotated perpendicular to the sacrotuberous ligament to visualise the lesser sciatic notch, just proximal to the ischial tuberosity, where obturator internus passes in a pulley-like manner (Fig. 1). The muscle's identity is confirmed by visualisation of medial movement of the muscle over the sciatic notch with gentle external rotation of the hip. The transducer position is maintained and, after application of antiseptic, the needle is inserted medial to the transducer until the tip lies in the muscle's medial aspect (Fig. 1). Placement is confirmed by a burst of EMG activity during hip external rotation.

Validation of intramuscular EMG recordings from obturator internus

Participants: Ten healthy individuals (5 male, age – 31 (8) years, height – 168(9) cm, weight – 69(12) kg) volunteered. Participants were excluded if they had any known neurological conditions, any known clotting disorders, or current hip, pelvic or back pain. The local Health Sciences Research Ethics Board approved the study and all procedures were conducted in accordance with the Declaration of Helsinki. Participants provided written informed consent.

EMG recordings: EMG recordings were made on the right side for all participants. A commercial bipolar fine-wire EMG electrode (2 strands of insulated wire with 5 mm uninsulated tips bent back at 5mm and 7 mm to form hooks; 50 mm x 25 gauge needle [Chalgren Enterprises Inc., USA] or custom-fabricated bipolar electrode [2 strands 75 µm Teflon coated stainless-steel wire, 1 mm Teflon removed, bent back at 1 and 3 mm to form hooks, 38 mm x 22 gauge hypodermic needle

(Terumo, USA)) was inserted into obturator internus. The type of electrode used depended on the depth of the obturator internus muscle as visualized using ultrasound imaging. A fine-wire electrode (custom-fabricated using 32 mm x 22 gauge hypodermic needle) was inserted into gluteus maximus 1 cm cranial to the obturator internus electrode. Fine-wire electrodes (either type) were inserted into other deep hip rotator muscles (quadratus femoris and piriformis) using standard sites similar to those reported for injection of local anaesthetic for piriformis [Smith et al., 2006] or standard clinical investigations for quadratus femoris [Lee et al., 2000], again with the type of electrode was selected on the basis of the depth of these muscles from the skin surface. The additional muscle sites were selected for comparison of EMG activity of obturator internus against other hip external rotator muscles. EMG data were bandpass filtered between 20-2000 Hz, amplified 1000 times and sampled at 4000 Hz using a custom modified Bagnoli EMG system (Delsys, USA) and EMGWorks software (Delsys, USA).

Procedure: In prone with the knee flexed, participants performed slow ramped isometric contractions into external rotation against manual resistance in an attempt to elicit differential recruitment of the four hip external rotator muscles. Contractions ramped from rest to maximum over 4-7 s. Participants were encouraged to perform pure rotation without extension of the hip.

Data analysis: Recordings were compared qualitatively and quantitatively. Qualitative analysis involved inspection of relative onsets of EMG and patterns of EMG amplitude modulation. Quantitative analysis involved fitting a linear regression of obturator internus data plotted against that from the other muscles. EMG data for each muscle were high pass filtered at 50 Hz to remove movement artefact [Moseley et al., 2003], full-wave rectified and then low pass filtered at 10 Hz to create a linear

envelope. The start and end of the ramp contraction were identified from obturator internus EMG. The period of contraction was divided into 25 epochs of equal duration and the root mean square (RMS) EMG amplitude was calculated for each. Separate regression lines were fitted to the epoch data for obturator internus and piriformis/quadratus femoris/gluteus maximus. Regression values, slopes and y-intercepts (latency between the two recordings) were recorded. Theoretically correlation coefficients between EMG channels near or equal to one, with concurrent intercept at or near zero would suggest that EMG was recorded from the same muscle whereas lower correlation coefficients and any significant deviation in the intercept would suggest that EMG activation was recorded from distinct muscles.

Statistical analysis: Regression values, slopes and y-intercepts for each regression line were compared between muscle pairs with a repeated measures analysis of variance (ANOVA).

Elucidation of obturator internus activation during maximal isometric hip efforts and simple tasks

Procedure: The same participants, instrumentation and recording parameters were involved in this part of the study. In prone with the hips in neutral alignment and, in separate trials, with the hip flexed 60° over the edge of the table, participants performed maximal hip efforts against manual resistance. Contractions were ramped over 3-5 s and maintained at maximum for 3 s with verbal encouragement. Two repetitions were performed with 30-60 s rest, which was considered sufficient because of the short contraction duration. Six tasks were performed in each position in random order: hip extension and flexion with the knee flexed (to reduce contribution of the hamstring muscles); hip abduction and adduction with the knees extended and

resistance provided by hands or a belt around both knees; and internal and external hip rotation with the knee flexed and resistance applied at the ankle.

In standing, participants rotated at the hips to the left and right (3 repetitions over 15 s). Participants maintained equal weight bearing through each leg and moved to the end of range of motion.

Data analysis: For maximal tasks, EMG amplitude and sequence of hip muscle activation was recorded. Root mean square (RMS) EMG amplitude was calculated for a 1-s period at rest and for the 1-s with the greatest EMG amplitude during the maximal voluntary contraction. RMS EMG amplitude at rest was subtracted and maximal EMG was identified from across tasks. This value was used to normalise EMG amplitude. EMG onset was identified visually as the first recruitment of a single motor unit from the resting state. The rank order of recruitment among the four muscles was recorded as a value of 1 to 4 for each repetition.

Statistical analysis: EMG amplitude during the maximum efforts was compared between Muscles, Directions and hip Angles using a repeated measures analysis of variance (ANOVA). The rank order of muscle onset was compared between Muscles within tasks using a Kruskal-Wallis ANOVA by ranks, and between Tasks using a Friedman ANOVA. The alpha level was set at $p < 0.05$.

Results

Validation of intramuscular EMG recordings from obturator internus

Figure 2 shows representative raw data from a slow ramped hip external rotation contraction to maximum with clear differentiation in activity of obturator internus from the other hip external rotator muscles. Clear differentiation in EMG onset and absence of additional activity recorded with the obturator internus electrode with activation of the other muscles provides evidence the recordings are derived

from different muscles with minimal crosstalk. Linear regressions show a strong correlation between muscle pairs (0.58 to 0.80), but with an offset (y-intercept) of 2.2 to 4.8 epochs (i.e. delay of 9-19% of the ramp duration) and a slope of 0.72 to 0.90 (Fig. 3). The regression value and slope tended to be lower for the relationship between the obturator internus and gluteus maximus EMG recordings than the other recordings, although this was not significant (Main effect – regression value: $p=0.11$; Main effect – slope: $p=0.052$). The latency between onset of obturator internus EMG and gluteus maximus was greater than that for piriformis (Main effect: $p=0.049$; post hoc: $p=0.02$). Taken together these data provide evidence that external rotator muscle EMG is related (because of functional similarities), but the recordings have features (latency between recordings and slope of the regression line of <1) that suggest the recording from the obturator internus electrode has minimal or no crosstalk from adjacent muscles.

Maximal contractions of hip muscles in different directions

EMG amplitude of each hip muscle varied between directions (Interaction: Muscle x Direction – $p=0.0003$; Fig. 4 and 5). All muscles had greater EMG amplitude with hip extension than the other directions (post-hoc all: $p<0.05$) and were minimally active with hip flexion, adduction and internal rotation. Obturator internus and quadratus femoris EMG demonstrated greater EMG activation in external rotation than abduction (post-hoc: $p<0.0001$), gluteus maximus was minimally active in abduction (EMG amplitude during abduction was not different to adduction [$p=0.30$]). Comparison of MVC-normalised EMG amplitudes between muscles indicated that obturator internus was less active than piriformis in abduction ($p=0.002$), more active than piriformis in external rotation (post-hoc: $p=0.004$) and less active than quadratus femoris in extension (post-hoc: $p=0.05$). Piriformis was

more active than all other muscles in abduction (post-hoc all: $p < 0.002$). Quadratus femoris was more active than piriformis in external rotation ($p = 0.025$).

The interaction between hip Angle and Direction was significant ($p < 0.0001$) but this did not differ among muscles (interaction: Angle x Direction x Muscle – $p = 0.89$). All muscles were more active during hip extension with the hip in neutral alignment than with 60° hip flexion (post hoc: $p < 0.0001$). With efforts in all other directions there was no difference between hip angles.

The sequence of onset of EMG activity differed between directions (Fig. 4 and 6). Figure 6 shows the average rank/order of EMG onset and the proportion of trials in which activity of a particular muscle occurred at a particular position in the order of recruitment. Obturator internus was more likely to be the first muscle recruited during external rotation (neutral hip - 80% trials [$p < 0.001$]; 60° hip flexion - 45% trials [$p = 0.0004$]) and abduction (neutral hip - 50% trials; $p < 0.001$; 60° hip flexion - 70% trials [$p = 0.0004$]) relative to the other muscles. When the force directions were compared for obturator internus, the mean onset rank was lower (earlier activation more likely) with external rotation and abduction than extension ($p = 0.0011$). All muscles were equally likely to be the first active in hip extension, regardless of hip position (neutral hip - $p < 0.56$; 60° hip flexion - $p = 0.27$). Gluteus maximums was more likely to be the last muscle active in external rotation (60% of trials) in 60° of hip flexion and when the rank onset was compared among tasks the onset was more likely to be earlier with extension than other tasks ($p = 0.0022$). There was no difference in onset for piriformis ($p = 0.08$) or quadratus femoris ($p = 0.098$).

Activation during hip rotation in standing

In standing with equal weight bearing between legs, obturator internus and the other muscles were inactive, but the muscles became active with hip rotation towards

the end of range of left rotation. All muscles were more active with rotation towards the left (right hip external rotation, ~4.2 to 7.5% maximum) than the right (0.2% maximum) (Main effect – Direction: $p=0.009$) and the EMG amplitude, relative to maximum, did not differ between muscles (Interaction – Direction x Muscle: $p=0.26$). Unlike hip rotation in prone, there was no difference in likelihood of any muscle being recruited first ($p=0.99$; Fig. 7).

Discussion

This study describes a viable EMG recording technique for the obturator internus muscle with minimal crosstalk from adjacent muscles. Furthermore, the data provide initial insight into recruitment of obturator internus in simple tasks. Notably, the muscle was more likely to be the first active during isometric hip abduction and external rotation torque, but active to a greater percentage of maximum during hip extension than other directions.

Valid method to make obturator internus EMG recordings

Although fine-wire electrodes reduce the potential for crosstalk, they do not eliminate it [Hodges et al., 2000]. It is difficult to quantify crosstalk in EMG recordings; techniques such as cross-correlation between recordings provide an unreliable estimate [Farina et al., 2004]. Here we estimated crosstalk qualitatively and quantitatively by consideration of the pattern of activation recorded from electrodes inserted into separate muscles to identify features that would provide evidence of distinct sources of activity. Presence of obturator internus EMG while other muscles remained inactive during ramped external rotation supports our conclusion regarding the selectivity of the recordings. Absence of changes in obturator internus EMG as other muscles were recruited provides additional evidence. Latency in the regression

and its slope of <1 provide objective evidence of unique features of the recordings with each electrode. We cannot exclude the possibility that some activity recorded with the obturator internus electrode was derived from adjacent muscles.

Confirmation would require silence in the obturator internus recording during isolated activation of other muscles. This was not possible due to the functional relationship between the muscles.

The gemmelli are possible sources of crosstalk but were not recorded.

Crosstalk from these muscles is unlikely as the electrode was inserted into obturator internus on the interior aspect of the pelvis, away from the gemmelli. The levator ani muscles might also contribute crosstalk to obturator internus EMG. These muscles originate within the pelvis and from fascia overlying the obturator internus. However these muscles do not generate hip torque and are unlikely to have been active during the tasks used in this study.

Recruitment of obturator internus in function

Conventional anatomy describes obturator internus as a hip external rotator [Shinohara, 1995] particularly in an extended hip position [Dostal et al., 1986; Gray, 1989], and an abductor [O'Rahilly, 1986; Woodburne, 1994] in a flexed hip position [Dostal et al., 1986; Gray, 1989], as well as role in hip stabilisation [Gray, 1989].

Others suggest hip horizontal abduction and even adduction [Basmajian et al., 1989].

In the absence of direct EMG recordings in humans these interpretations of function have been derived from anatomy. Obturator internus EMG recorded during external rotation and abduction support the most obvious predictions. The preference for its activation prior to the other muscles could be due to its: 1) greater efficiency because of its moment arm; 2) greater potential to generate smooth force increments at low forces (perhaps because of a greater proportion of small motor units); or 3)

preferential activation related to a presumed role in hip stabilisation (see below).

There is insufficient data in humans to consider the first two possibilities, although cat data imply a high proportion of slow twitch motor units [Roy et al., 1997].

Although not suggested in anatomical texts or predictions from studies of moment arms [Dostal et al., 1986], the greatest activity of obturator internus was recorded during hip extension. This does not imply a greater contribution to hip extension, as greater EMG may be required due to mechanical inefficiency in this direction. Similarly, greater activity in external rotation than abduction could imply greater contribution to that direction, but again differences in mechanical advantage cannot be excluded. A role of the muscle in hip adduction is refuted.

The role of obturator internus in hip stabilisation [O'Rahilly, 1986; Hall-Craggs, 1990] or holding the femoral head in the acetabulum [Morris, 1953; Moore, 1985] is based on the muscle's fibre orientation and size. Gray [1989] defined obturator internus (and other short hip rotators) as "adjustable ligaments" for all hip positions. Cat anatomical and histochemical work supported this notion with evidence of design features considered ideal for hip control: short mean fibre lengths; small fibre pennation angles; small physiological cross-sectional area; and a high proportion of slow twitch fibres, [Roy et al., 1997]. Human data of short fibre length [Friederich et al., 1990] has been interpreted to imply function in hip joint stabilisation rather than torque generation [Ward et al., 2010]. It has been argued that a role in hip stabilisation would be supported if the muscle is active during many behaviours [Stern et al., 1993] with forces in different directions, rather than only predictable muscle actions. Absence of activity in quiescent bipedal stance (except at the end of range of hip rotation) and limitation of activity to specific directions of hip force in the present study and earlier work in non-human primates [Stern et al., 1993], suggest

a generalised role in regulation of femoral position for hip stabilisation is unlikely. Taken together with data of the orientation of the muscle fibres, our data imply that obturator internus supports the hip joint but only when torques are applied in the specific directions in which the muscle is active.

The function of many hip muscles has been argued to change as a function of hip position. Although obturator internus maintains an external rotation moment arm throughout hip flexion, it decreases with increasing flexion [Dostal et al., 1986; Delp et al., 1999]. Despite this change, we showed no change in EMG activity between external rotation efforts in a neutral or flexed hip. However, all muscles were more active during hip extension in neutral hip alignment.

Conclusion

This study describes a viable and valid technique to record obturator internus EMG and provides the first direct evidence of activation in simple functions. Data can be interpreted to suggest that a role as an “adjustable ligament” according to its muscle fibre anatomy would be limited to situations in which torques are applied in specific directions, rather than a generalised role.

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Captions to Illustrations

Figure 1 *Electrode insertion method.* A. Anatomy of the obturator internus relative to the bony landmarks of pelvis, sacrotuberous ligament and sciatic nerve. The placements of the ultrasound transducer used to generate the images in the lower panel are shown and the location for needle insertion is indicated with the '*'. B. Ultrasound image perpendicular to obturator internus. C. Ultrasound image along fibres of obturator internus showing muscle passing from interior of pelvis (left) and over the lesser sciatic notch to the exterior surface of the pelvis. The approximate location used for insertion of the needle is shown.

Figure 2 *Gradual ramped isometric hip external rotation contractions.* A. Representative raw data with the onset of EMG activity of each muscle indicated with an arrow and that of obturator internus also shown with the dotted line for comparison with the other muscles. B. Regression lines fitted to the relationship between obturator internus and each of the other muscles for the same trial as shown in panel A. The regression value and equations are shown for this representative recording.

Figure 3 *Group mean regression value, slope and y-intercept for the regression lines fitted to the relationship between obturator internus (OI) EMG and that of gluteus maximus (GMvOI), piriformis (PFvOI) and quadratus femoris (QFvOI).* Regression lines were fitted to data epochs of 25-ms from the onset to end of obturator internus EMG during the gradual ramped increase of isometric external rotation torque. Mean and standard deviation are shown.

Figure 4 *Representative raw EMG data for maximal hip external rotation, abduction and extension against manual resistance.* The onset of EMG activity of each muscle is indicated with an arrow and that of obturator internus is also shown with the dotted line for comparison with the other muscles. All recordings are from

the same participant and trial. Note the onset of the EMG recorded from obturator internus occurs prior to the other muscles in each direction of isometric force.

Figure 5 *Group mean EMG amplitude recorded during maximal isometric efforts for each task. Data are shown for each muscle, each contraction direction and each hip position (i.e. neutral position and 60° of hip flexion). Standard deviations are shown.*

Figure 6 *Group means for rank order of recruitment of the hip muscles during isometric contractions in each direction. A. Average rank across participants for each muscle. B. Percentage of trials in each rank position. In A note the lower mean rank for obturator internus in abduction and external rotation which indicates a high prevalence of being the first recruited muscle. Similarly in B note the high percentage of trials in which obturator internus is recruited first in abduction and external rotation.*

Fig. 7 *Group mean (A) EMG amplitude and (B) rank onset of each muscle during hip rotation in standing. All muscles were active to a greater percentage of maximum with rotation to the left as compared to the right. Standard deviation is shown.*

References

- Basmajian JV, Slonecker C. Grant's method of anatomy. Baltimore: Williams and Wilkins, 1989
- DeLancey JO. Structural support of the urethra as it relates to stress urinary incontinence: the hammock hypothesis. *Am J Obstet Gynecol* 1994;170(6):1713-20
- Delp SL, Hess WE, Hungerford DS, Jones LC. Variation of rotation moment arms with hip flexion. *J Biomech* 1999;32(5):493-501
- Dostal WF, Soderberg GL, Andrews JG. Actions of hip muscles. *Physical Therapy* 1986;66(3):351-61
- Farina D, Merletti R, Indino B, Graven-Nielsen T. Surface EMG crosstalk evaluated from experimental recordings and simulated signals. Reflections on crosstalk interpretation, quantification and reduction. *Methods of Information in Medicine* 2004;43(1):30-5
- Friederich JA, Brand RA. Muscle fiber architecture in the human lower limb. *Journal of Biomechanics* 1990;23(1):91-5
- Gray H. Muscles and fascia. In: Williams P, Warwick R, Dyson MBannister I. *Gray's anatomy*. Edinburgh, Churchill Livingstone. 1989.
- Hall-Craggs E. *Anatomy as a basis for clinical medicine*. Baltimore: Urban and Schwarzenberg, 1990
- Hodges PW, Gandevia SC. Pitfalls of intramuscular electromyographic recordings from the human costal diaphragm. *Clinical Neurology* 2000;111(8):1420-24
- Hulme J, Nevin G. Comparison of traditional kegel exercises with obturator internus exercise protocol for treating bladder incontinence. In *Proceedings: American Physical Therapy Association Combined Sections Meeting*, Seattle, WA, USA. 1999

Lee H, Delisa J. Surface Anatomy for Clinical Needle Electromyography. New York: Demos Medical Publishing, Inc, 2000

Moore KL. Clinically Orientated Anatomy. Baltimore: Williams & Wilkins Co., 1985

Morris H. The Musculature. In: Schaeffer J. Morris' Human Anatomy. New York, McGraw-Hill. 1953.

Moseley GL, Hodges PW, Gandevia SC. External perturbation of the trunk in standing humans differentially activates components of the medial back muscles. *Journal of Physiology* 2003;547:581-7

O'Rahilly R. Gardner-Gray-O'Rahilly: Anatomy. Philadelphia: WB Saunders, 1986

Roy RR, Kim JA, Monti RJ, Zhong H, Edgerton VR. Architectural and histochemical properties of cat hip 'cuff' muscles. *Acta anatomica* 1997;159(2-3):136-46

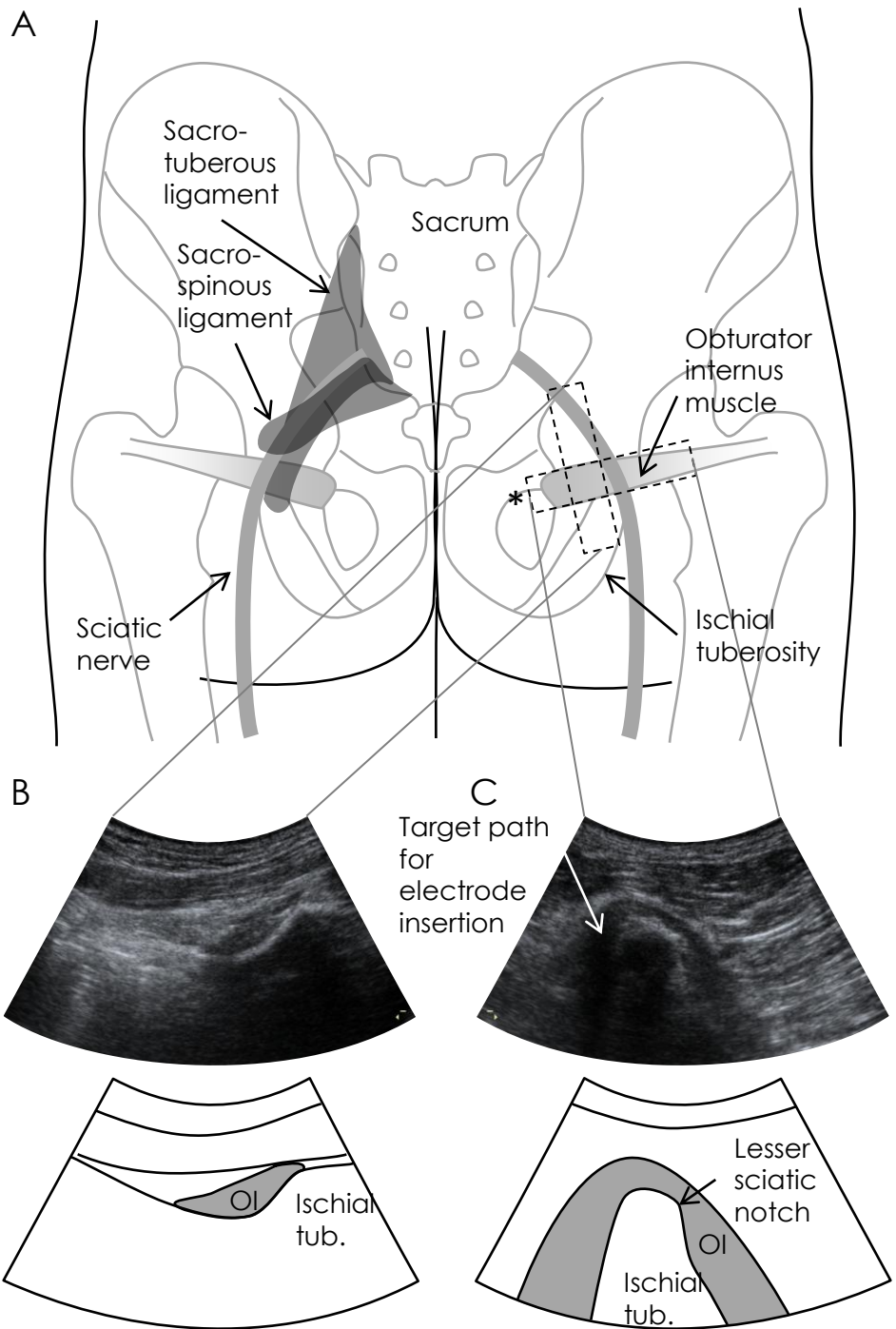
Shinohara H. Gemelli and obturator internus muscles: different heads of one muscle? *Anatomical Record* 1995;243(1):145-50

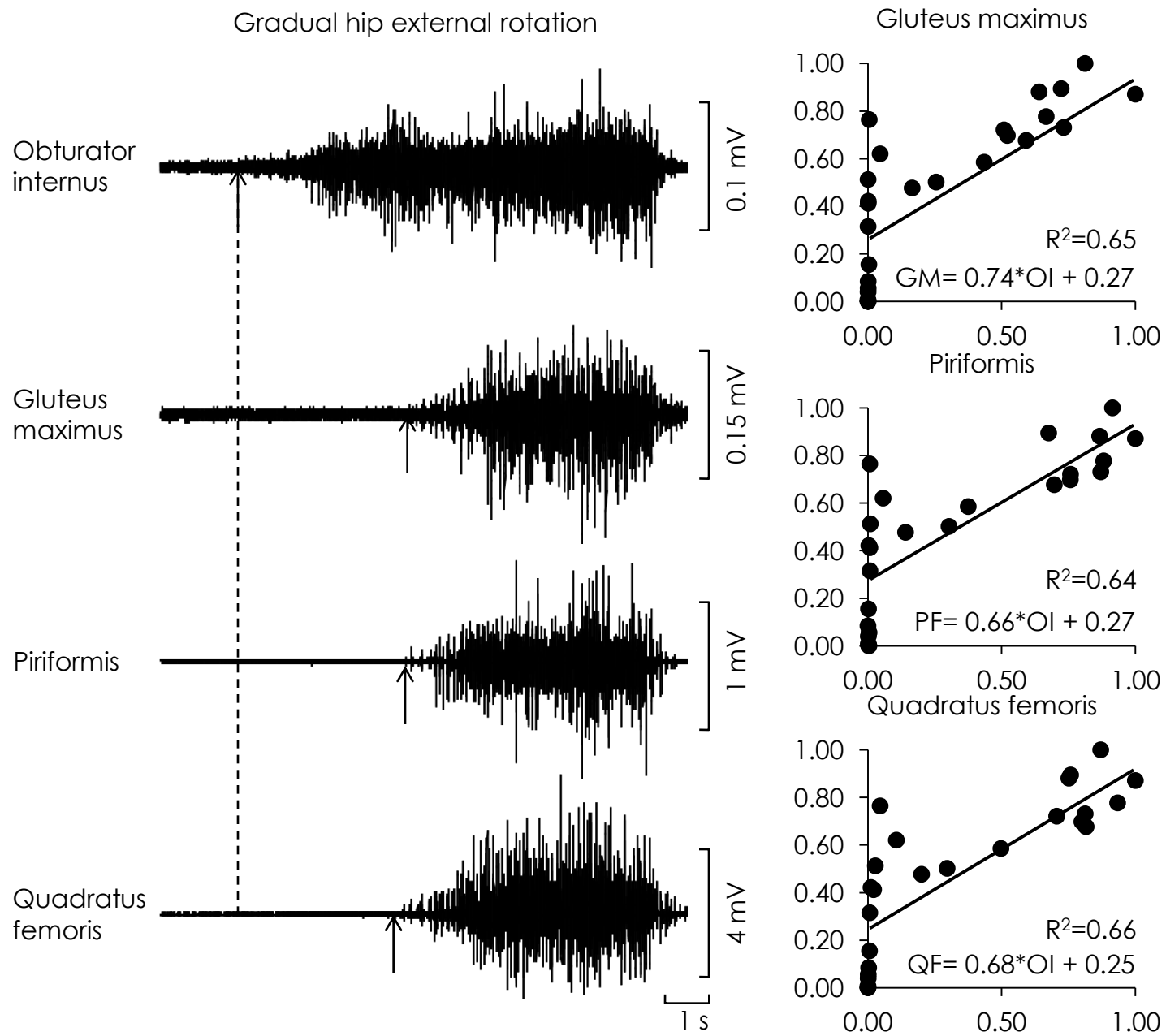
Smith J, Hurdle MF, Locketz AJ, Wisniewski SJ. Ultrasound-guided piriformis injection: technique description and verification. *Archives of Physical Medicine and Rehabilitation* 2006;87(12):1664-7

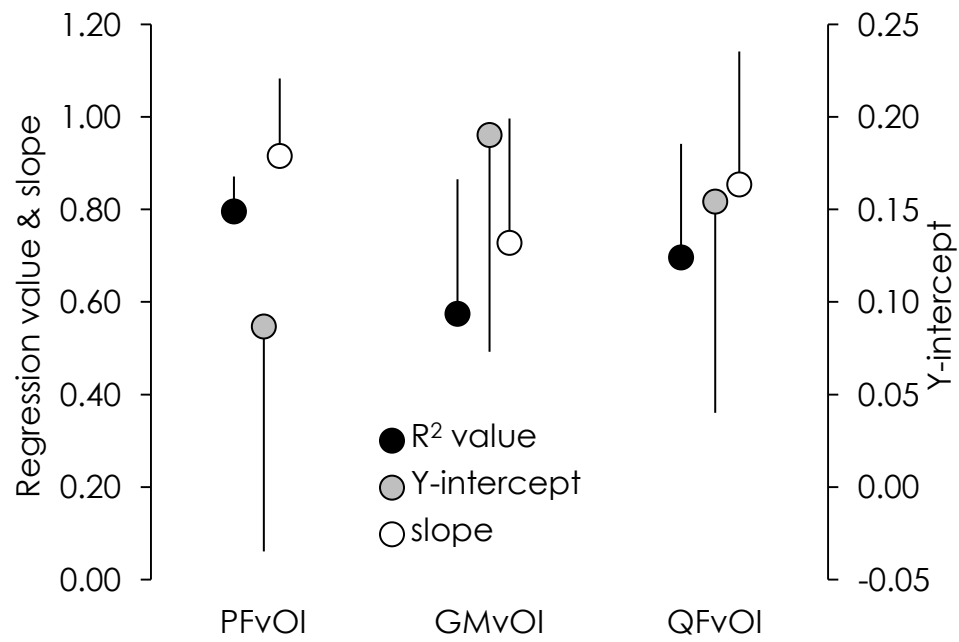
Stern J, Larson S. Electromyographic study of the obturator muscles in non-human primates: implications for interpreting the obturator externus groove of the femur. *Journal of Human Evolution* 1993;24:403-27

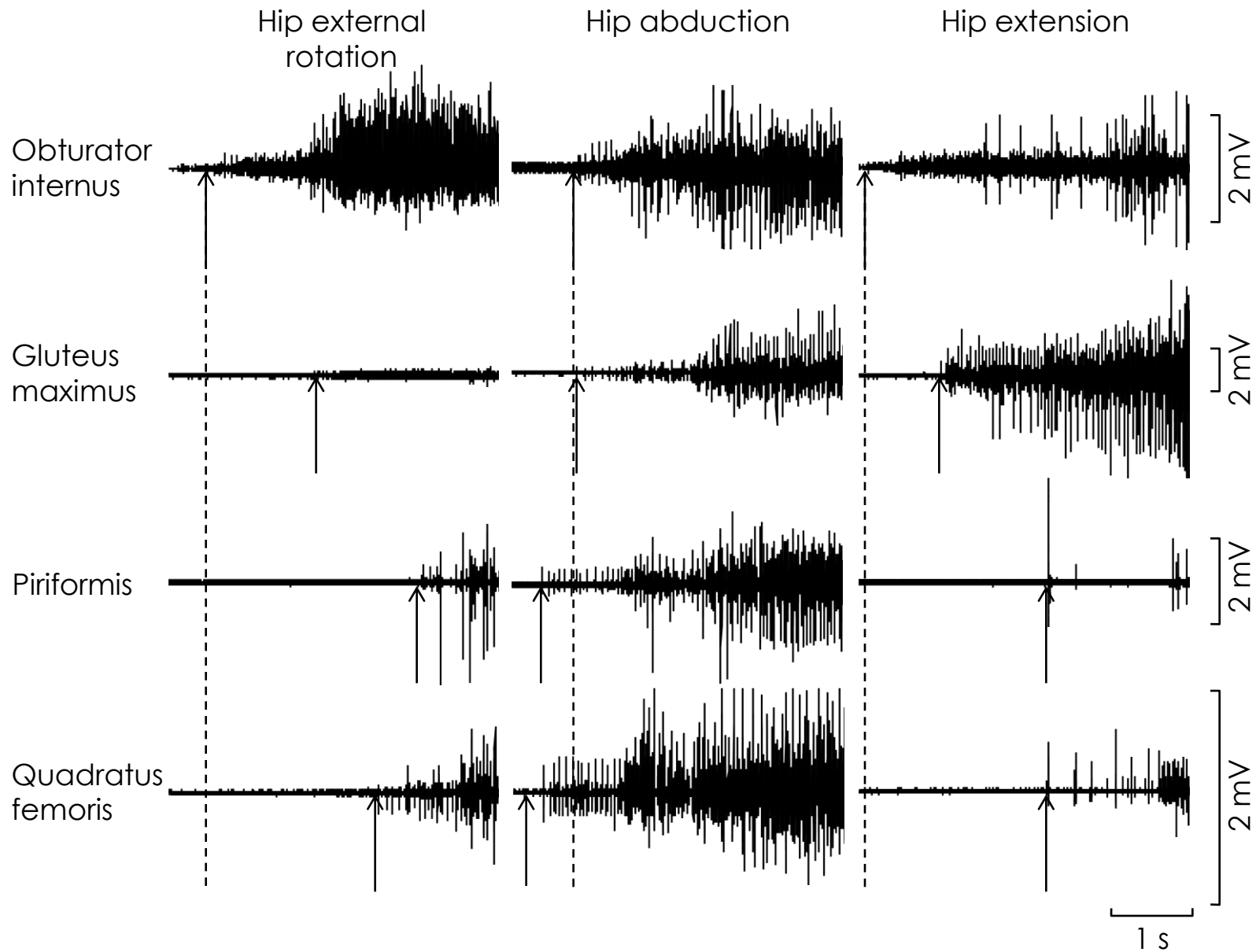
Ward SR, Winters TM, Blemker SS. The architectural design of the gluteal muscle group: implications for movement and rehabilitation. *Journal of Orthopaedic and Sports Physical Therapy* 2010;40(2):95-102

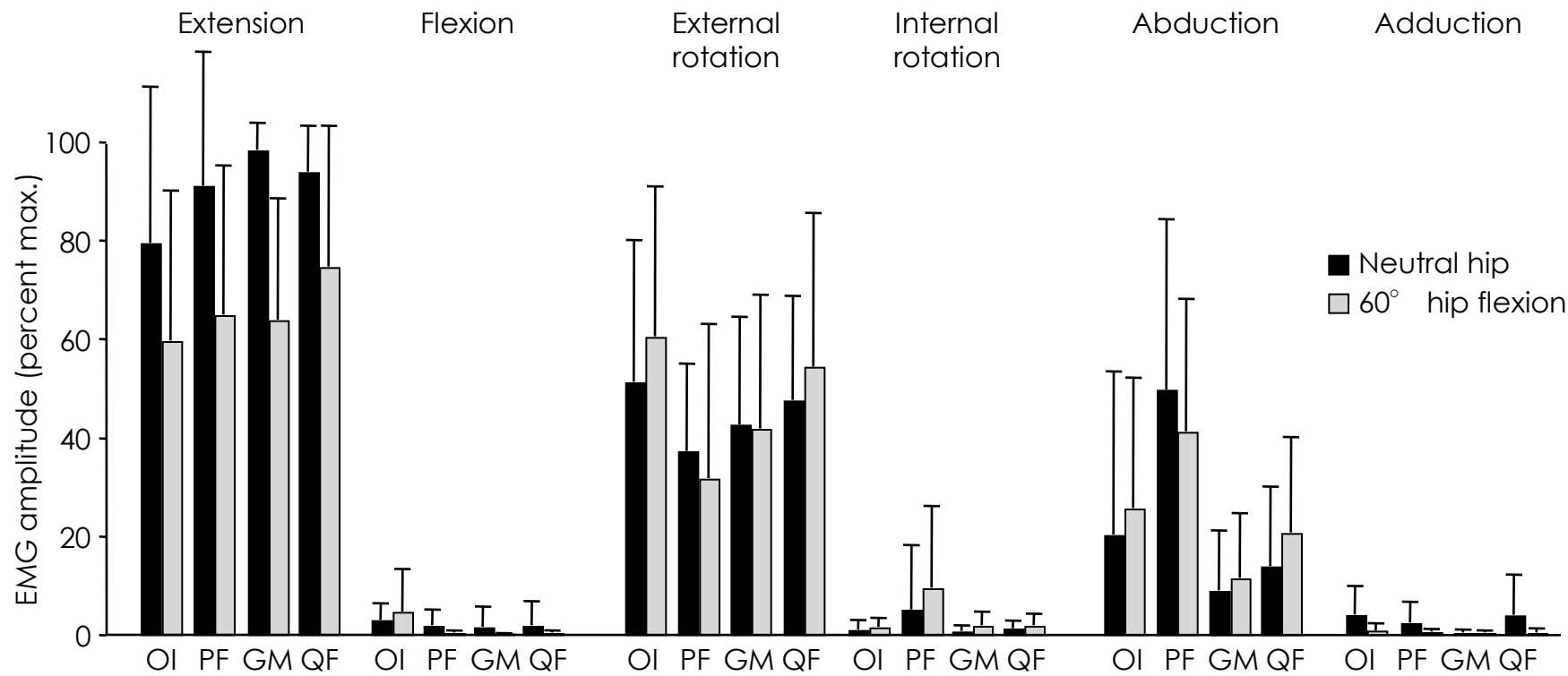
Woodburne R. Essentials of Human Anatomy. New York: Oxford University Press 1994

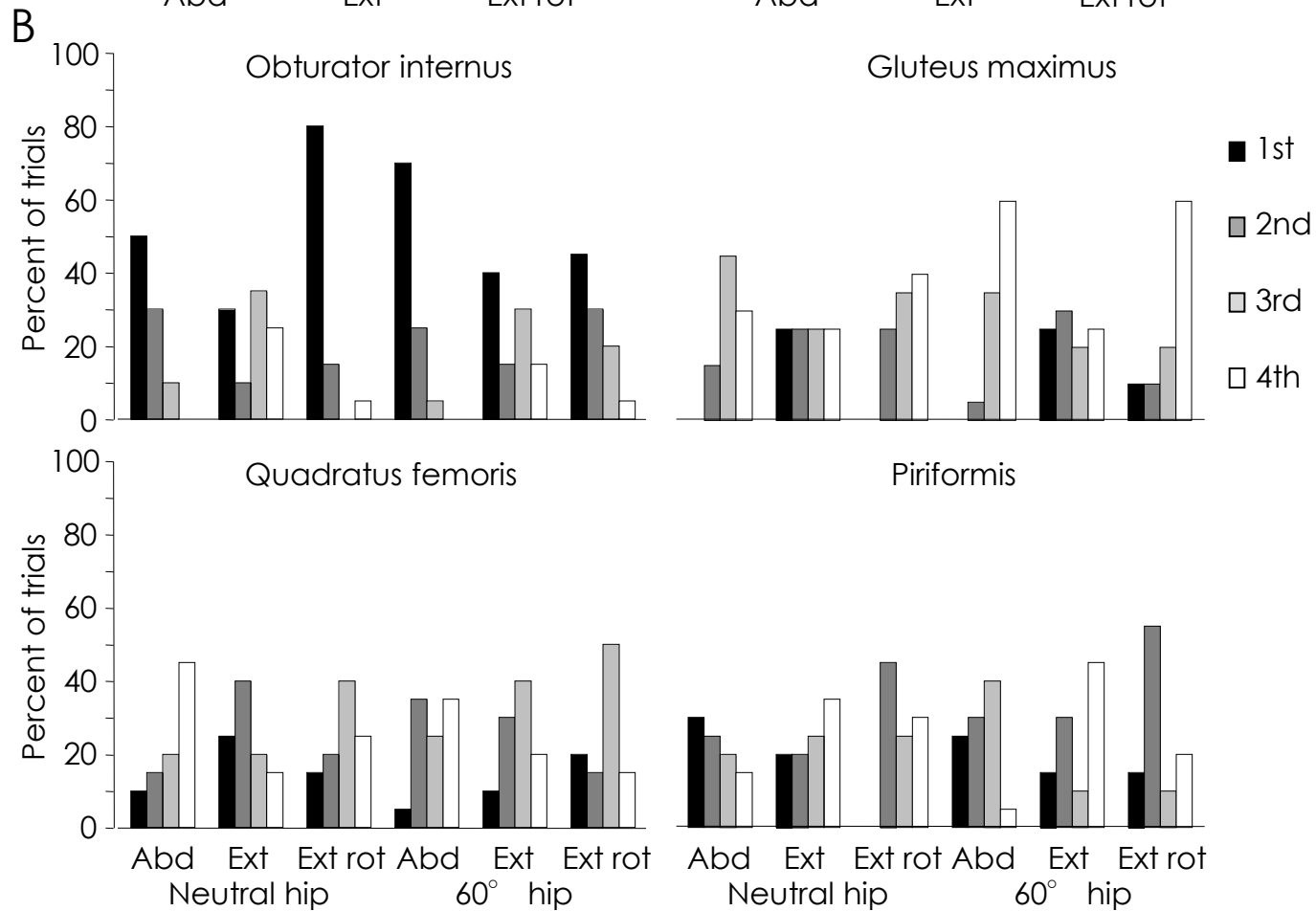
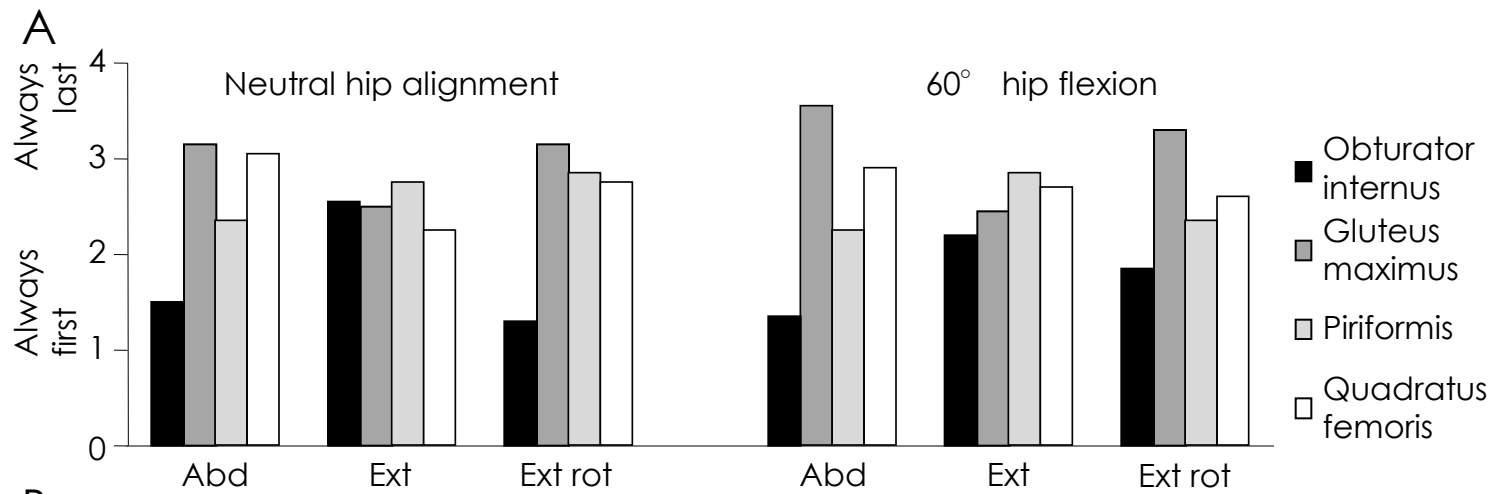


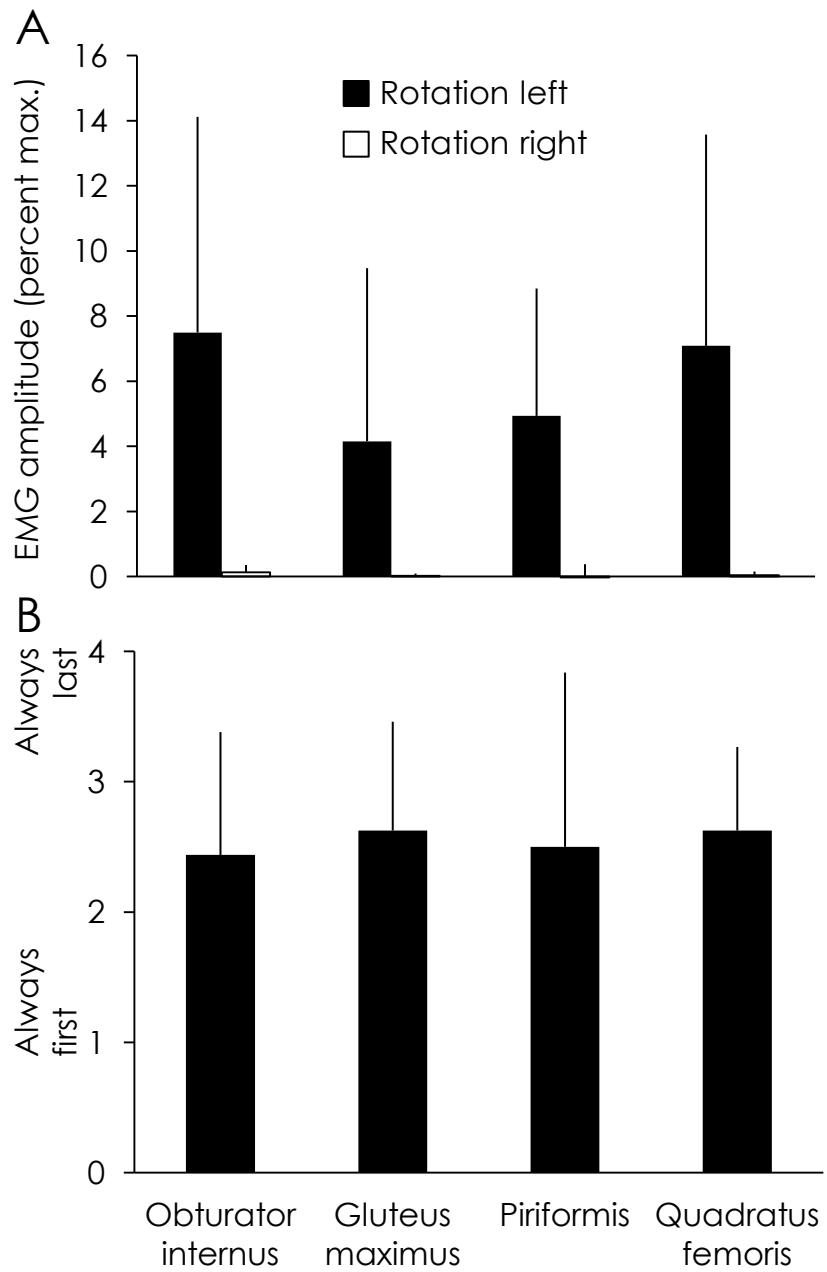












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Paul Hodges PhD MedDr DSc BPhy(Hons) FACP is an NHMRC Senior Principal Research Fellow and Directs the NHMRC Centre for Clinical Research Excellence in Spinal Pain, Injury and Health. Paul has 3 doctorates; one in Physiotherapy and two in Neuroscience. His research blends these skills to understand pain, control of movement, and the multiple functions of trunk muscles including spine control, continence, respiration and balance. His large multidisciplinary Research Centre bridges the gap between basic science and clinical practice. He has received numerous international research awards (including 2006/2011 ISSLS Prize), published >270 papers and book chapters and presented >120 keynote lectures in >30 countries. He is the incoming president of the International Society for Electrophysiology and Kinesiology (ISEK) and chaired the 2012 conference of ISEK in Brisbane, Australia.

Linda McLean

Linda McLean is a Full Professor in the School of Rehabilitation Therapy at Queen's University. She received her BSc in Physiotherapy from McGill University in 1990, and her MSc (Electrical Engineering) and PhD (Interdisciplinary studies in Biomedical Engineering) in 1995 and 1998 respectively from the University of New Brunswick in Canada. Her research work sits at the interface between health sciences and engineering, where she studies chronic muscle disorders using mechanical and neurophysiological assessment approaches. Her work mainly deals with women's health issues such as pelvic floor muscle function and dysfunction, and pregnancy related neuromusculoskeletal issues. Dr. McLean is an Associate Editor of the Journal of NeuroEngineering and Rehabilitation and is a member of the Editorial Board of the Journal of Electromyography and Kinesiology. She has been a member of the ISEK Executive committee and co-chaired the ISEK 2008 conference in Niagara Falls, Ontario.

Joanne Hodder

Joanne N. Hodder received her PhD in Biomechanics from McMaster University in 2012. She held a Post Doctoral Fellowship in the School of Rehabilitation Therapy at Queen's University during 2012 and is currently a Post Doctoral Fellow at McMaster University. Her research examines on neuromuscular coordination and joint mechanics with a focus on understanding how musculoskeletal injuries alter these factors.

Paul Hodges



Linda McLean



Joanne Hodder



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