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1 **MUSCLE THICKNESS MEASUREMENTS TO ESTIMATE GLUTEUS MEDIUS**
2 **AND MINIMUS ACTIVITY LEVELS**

3

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17

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3
4
5 **Abstract**

6 The clinical assessment of gluteus medius and minimus force sharing requires
7 non-invasive measurements of individual activity levels. Do ultrasound
8 measurements of change of muscle thickness substitute invasive
9 electromyography (EMG)? Isometric hip abduction in 20-80% MVIC was
10 measured using dynamometry, M-mode ultrasound for gluteus medius and
11 minimus thickness and EMG using (1) surface electrodes on gluteus medius,
12 n=15, (2) fine-wire electrodes in deep gluteus medius and minimus, n=6.
13 Gluteus medius thickened by 5.0 (SD 2.5) mm at 80% MVIC while gluteus
14 minimus thickness was constant in the surface EMG study and decreased by
15 1.6 (SD 1.6) mm at the more ventral location in the fine-wire EMG study.
16 Thickness change of gluteus medius enabled prediction of torque (r^2 0.66) and
17 of surface EMG amplitude (r^2 0.57). Surface EMG enabled higher torque
18 prediction (r^2 0.84) than thickness change. Thickness change of gluteus
19 minimus did not enable a practically relevant estimation of torque production.
20 Ultrasound examination revealed a differential thickening behaviour of gluteus
21 medius and minimus which enabled estimation of isometric torque production
22 only for gluteus medius but with lower precision than surface EMG.

MUSCLE THICKNESS MEASUREMENTS TO ESTIMATE GLUTEUS MEDIUS AND MINIMUS ACTIVITY LEVELS

Introduction

In hip joint pathology, a redistribution of muscle activity, specifically of force sharing between superficial and deep hip abductors, has been suggested (Sims et al., 2002, Grimaldi et al., 2009). Differential activity between abductor muscles, muscle parts and levels of depth has been documented (Soderberg and Dostal, 1978, Kumagai et al., 1997). Targeted physiotherapy may require a distinction between gluteus medius and gluteus minimus activity. Current methods to assess force sharing between superficial and deep muscles rely on invasive fine-wire electromyography (EMG), which is not applicable in a rehabilitation setting. Additionally, the potentially painful electrode insertion may affect motor behaviour (Kadaba et al., 1985, Chimera et al., 2009). These limitations emphasize the need for a non-invasive assessment of deep muscle activity.

Ultrasound imaging (US) has been used to measure changes of cross-sectional area (Delaney et al., 2010), muscle shape (Lee et al., 2007), muscle thickness (Worsley et al., 2014), fascicle length (Reeves et al., 2006) and pennation angle (Samukawa et al., 2011) with graded activity. The measurement with the broadest applicability is muscle thickness.

The relationship between the level of isometric activity and the change of muscle thickness is different between muscles. A curvilinear relationship has been described for the biceps, brachialis, tibialis anterior, transversus abdominis and obliquus internus muscles (Hodges et al., 2003, Shi et al., 2008). A linear relationship has been described for the lumbar multifidus (Kiesel et al., 2008), transversus

1 abdominis (McMeeken et al., 2004) and obliquus externus, but for the latter only in
2 isometric trunk rotation (John and Beith, 2007). An inconsistent thickening behaviour
3 of obliquus externus has been demonstrated during abdominal hollowing (Hodges et
4 al., 2003, John and Beith, 2007) while only minimal, curvilinear thickening has been
5 observed in rectus femoris (Delaney et al., 2010). Constant thickness during graded
6 isometric activity has been reported for gastrocnemius medialis (Narici et al., 1996).
7 Intra-abdominal pressure (Hodges, 2005), increasing pressure of adjacent muscles
8 (Delaney et al., 2010) and differences in connective tissue elasticity (Hodges, 2005)
9 have been discussed as causing diverse thickening behaviours in muscles. The
10 relationship between activity level and thickness change needs to be determined for
11 a muscle before thickness change can be interpreted.

12 This investigation aimed to investigate the prediction of the level of gluteus
13 medius and minimus sustained, isometric activity by US measured change of muscle
14 thickness in comparison to surface and fine-wire EMG amplitude.

15

16 **Materials and Methods**

17 In the main study, graded, isometric hip abduction was monitored by
18 dynamometry, M-mode US and surface EMG (sEMG) to compare levels of hip
19 abduction torque to gluteus medius and minimus thickness change and to amplitude
20 of gluteus medius sEMG. Data were complemented by a fine-wire (fw)EMG study to
21 compare gluteus minimus thickness to fine-wire EMG amplitude. The following
22 paragraphs describe the methods of the main study and identify the aspects in which
23 the methods of the fwEMG study differed.

24

1 *Subjects.* Volunteers were recruited in the School of Physiotherapy. Exclusion
2 criteria were hip pain, history of hip pathology or general musculoskeletal disease.
3 Ethics approvals were obtained from the institutional Human Research Ethics
4 Committee. Subjects provided informed consent.

5
6 *Procedure.* In supine lying, isometric right hip abduction was performed
7 against a dynamometer which was fixed to the plinth and had contact to the distal
8 lateral thigh, while the left side of the pelvis was stabilized against a fixed plate (Fig.
9 1). Subjects practised isometric hip abduction with the foot pointing vertically and
10 without flexing the hip. The mean of three repetitions of maximal voluntary isometric
11 contraction (MVIC) served to determine individual torque production. A random
12 sequence of trials at four torque levels was performed in a standardized procedure,
13 which included three repetitions of 20%, 40% and 60% of MVIC and two repetitions
14 of 80% MVIC, sustained for four seconds, with relaxation times of 10, 20, 30 and 45
15 s, respectively. A custom-programmed application (LabVIEW V8.2.1, National
16 Instruments, Texas) enabled visual feedback of actual and target torque levels.

17 [Insert Figure 1]

18 *Dynamometry.* Compressive force was sampled at 1000 Hz. Dynamometer
19 data (Mecmesin AFG-500N, Slinfold, UK) were low-pass filtered with a zero lag 4th
20 order Butterworth filter at 40 Hz. The averaged root mean square (RMS) amplitude
21 was determined for the 2nd second of sustained activity. Subjects tended to
22 overshoot the low force level and undershoot the high level; RMS amplitude was
23 normalized to the mean of the 40% trials. Normalization accounted for individual
24 differences in bony lever lengths; therefore normalized torque is reported.

1
2 *Ultrasound.* Thickness change of gluteus medius and minimus was monitored
3 using M-mode US, which enables reliable measurements of muscle thickness (Bunce
4 et al., 2002, McMeeken et al., 2004). M-mode US reflects displacement of sound-
5 reflecting interfaces (e.g. perimyseum) in high temporal resolution. As muscle activity
6 is associated to fascicle motion (Karamanidis et al., 2005), M-mode enables the
7 visual control of muscle relaxation (Dieterich et al., 2014). US was performed on an
8 Antares 4.0 (Siemens Medical Solutions, USA) with a 4-9 Hz linear probe (VFX9-4),
9 38 mm footprint and highest sweep speed. In longitudinal scanning, the M-mode
10 beam was set cranial to the hip joint capsule (Fig. 2a). The scanning location was
11 determined on the lower half of a line which connected the tip of the greater
12 trochanter to the anterior quarter of a line which directly connected the anterior and
13 posterior iliac spines (Fig. 2). The transducer was housed in a foam block at an angle
14 of 20°, at which the clearest image of hip abductor fasciae had been achieved in
15 preliminary tests. The foam block restricted rotary movement of the transducer;
16 individual adjustments in transducer tilting and rocking (Ophir et al., 1999) were
17 allowed by the medium density foam, to optimise the delineation of Gmin fascia and
18 iliac periosteum.
19 US recordings were captured onto video (Panasonic NV-MX 500A, Secaucus, USA).
20 M-mode provided traces of muscle thickness over 1.8 s per image which enabled
21 safe identification of sustained activity in high temporal resolution of 3.8 ms per pixel.
22 Still images showing the 2nd second of sustained activity were cut for
23 measurements. For each subject, randomly ordered 'stacks' of images in relaxation
24 and sustained activation were enlarged to 200% and measured off-line using ImageJ

1 software (version 1.40; rsb.info.nih.gov/ij/). Muscle relaxation was confirmed twofold,
2 by EMG for gluteus medius and by M-mode US for gluteus medius and gluteus
3 minimus (Dieterich et al., 2014). Muscle thickness was measured from the inner
4 edges of the fascias (Whittaker, 2007, p. 99). The assessor was blinded as to the
5 level of muscle activation. Thickness change is the difference between relaxed and
6 activated thickness, both including measurement error. To reduce error summation,
7 averaged relaxed muscle thickness was used as baseline reference.

8
9 *Electromyography.* EMG was recorded using an Octopus AMT-8 EMG system
10 (Bortec Electronics Inc., Calgary, Canada), input impedance 10 GOhm, common
11 mode rejection of 115 dB at 50 Hz. SEMG was sampled at 1000 Hz, bandwidth of 10-
12 1000 Hz, using pre-gelled, round 8mm Ag-AgCl surface electrodes (3M) and 22 mm
13 inter-electrode distance. The ground electrode was attached to the lateral ribs.
14 Following skin preparation, electrodes were positioned on the same gluteus medius
15 part as measured by US (Fig. 2). Raw signals were pre-amplified 500 times,
16 amplified, fed into a computer with an input amplitude range of +10 V, 16bit digitized
17 and displayed on-screen (LabVIEW V8.2.1, National Instruments, Texas). The
18 averaged RMS EMG amplitude (Merletti et al., 1999) of the demeaned and zero-lag
19 band-pass filtered (10-400 Hz) signals was determined for the 2nd second of
20 sustained activity, allowing for 60 ms electromechanical delay relative to the time-
21 window of RMS torque amplitude. (Howatson et al., 2009). RMS amplitude was
22 normalized to the mean of the 40% trials.

23 *[Insert Figure 2]*

1 *Synchronization.* Synchronization of torque, US and EMG data was achieved
2 by splitting a trigger signal to synchronously start dynamometer and EMG recordings
3 and create a visual signal on the concurrent video frame (Event Synchronization Unit,
4 PEAK Performance Technologies Inc., Centennial, CO, USA). If in the 2nd second
5 performance of sustained activity was unstable, the analysed data window was
6 adjusted accordingly in EMG, M-mode and dynamometry data.

7
8 *Method differences in the fine-wire EMG study.* Due to ethical requirements,
9 fw-electrode insertion was restricted to 'Hoffstetter's triangle', an area void of larger
10 nerves and vessels slightly cranial and ventral to the recording area of the main study
11 (Fig. 2). The M-mode beam was positioned in the right half of the image
12 corresponding to the main muscle bulk (Fig. 2b). M-mode US was recorded using a
13 Toshiba Xario XG (Toshiba, Medical Division, Australia) using a linear probe at 6.2
14 MHz (PLT-704SBT). M-mode traces displayed muscle thickness over 1.4 s per image
15 with a temporal resolution of 2.2 ms per pixel. Still images of full trial duration were
16 sampled on the US system and stored in .tiff format. FwEMG was recorded at a
17 sampling rate of 2000 Hz using custom-prepared, differential, Teflon-coated fw-
18 electrodes (California Wire Company, Grover Beach, USA) with a diameter of 0.075
19 mm. In a sterile procedure under US guidance, electrodes were inserted obliquely
20 into the deep gluteus medius and minimus muscles. FwEMG signals were band-
21 pass-filtered between 10-900 Hz. Synchronization of US and fwEMG data was
22 achieved by a split trigger signal which started dynamometry and EMG recording and
23 produced a spike in the ECG signal trace of the US system. With fw-electrodes
24 inserted, subjects were reluctant to exert full force. Three ramp activations were used

1 to determine individual maximum levels which were assumed to correspond to the
2 80% level of the main study.

3
4 *Statistics.* Intra-tester reliability of thickness measurements on the same scans
5 in relaxation and activation was established on randomly chosen images, 87 (53%) of
6 the main study and 42 (76%) of the fwEMG study, by ICC_{3,1}, mean difference,
7 standard deviation (SD) and minimal detectable change (MDC, $MDC_{95} =$
8 $SEM \cdot \sqrt{2} \cdot 1.96$) (Donoghue et al., 2009) with a two week interval between re-
9 measuring the same images. Intra-subject variation of measurements of relaxed
10 muscle thickness was described by SD and MDC. Thickness change at high-level
11 activation, 80% MVIC in the main study and maximal activation in the fwEMG study,
12 was expressed as percentage of relaxed thickness. Prediction of torque from
13 percentage of thickness change and from EMG amplitude was estimated by the
14 coefficient r^2 , comparing linear and exponential regression models. Normal
15 distribution of residuals was checked by histograms and p-and-p plots. Homogeneity
16 of variance was confirmed by plotting standardized predicted values against
17 standardized residuals (Field, 2009). Significance was set to $\alpha=0.05$. Results are
18 presented in mean (SD).

19

20 **Results**

21 In the main study, fifteen subjects (nine females) aged 28 (7.9) years
22 participated. In the fwEMG study, six subjects (one female) aged 39 (7.9) years
23 participated. Data inclusion exceeded 90% (Table 1). Good measurement reliability
24 on the same scans was indicated by ICCs>0.86 (Table 2). Differences between linear

1 and exponential models were below 4% with a slight preference for linear regression.
2 The text reports linear regression results, tables include both models.

3 *[Insert Tables 1 and 2]*

4 *Estimation of gluteus medius activity level*

5 In the main study, gluteus medius thickened at 80% MVIC by 5.0 (2.5) mm,
6 20.6% of relaxed thickness (Fig. 3). Torque was significantly correlated with the
7 percentage of Gluteus medius thickening, r 0.80. Gluteus medius thickness change
8 enabled estimation of torque, r^2 0.66 (Table 4a) and of sEMG amplitude, r^2 0.57. In
9 comparison, sEMG amplitude allowed for torque prediction with r^2 0.84. The fwEMG
10 study confirmed the findings of the main study (Table 3b).

11

12 *Estimation of gluteus minimus activity level*

13 In the main study, gluteus minimus became thinner by 0.2 (1.9) mm, 1.1%, at
14 80% MVIC (Fig. 4 and Table 3a). Correlation between torque and percentage of
15 thickness change was weak, r 0.05 with r^2 0.12 (Table 4a, Figure 5). In the fwEMG
16 study, gluteus minimus became thinner by 1.6 (1.6) mm, 8.2% at maximal activation
17 (Table 3b). All subjects indicated a negative correlation, r -0.66, significant in four
18 subjects. Gluteus minimus thickness change enabled estimation of torque, r^2 0.46
19 (Table 4b) and of fwEMG amplitude r^2 0.42. In comparison, fwEMG amplitude
20 allowed for torque prediction with r^2 0.89.

21 *[Insert Figures 3, 4 and 5. Tables 3a) and b) and 4a) and b) may be inserted here to*
22 *support the conclusions by single subject data, if considered valuable]*

1 **Discussion**

2 This research investigated the estimation of sustained, isometric hip abductor
3 torque by US measured thickness changes. The results document the predictability
4 of torque production by gluteus medius thickness change, however, with lower
5 precision than sEMG. Torque production of the hip abductor synergy was not
6 predictable from gluteus minimus thickness change. At the measured locations, the
7 two hip abductors exhibited a principally different thickening behaviour during
8 isometric contractions.

9

10 *Predictability of gluteus medius and minimus activity levels*

11 The determination coefficient r^2 quantifies the proportion of variance of the
12 dependent variable (torque level or EMG amplitude) that is explained by the predictor
13 (US measurement) (Portney and Watkins, 2000, p. 519). Thus, 66% of variance in
14 torque and 57% of variance in EMG amplitude was explained by gluteus medius
15 thickness change. In contrast, EMG amplitude explained 84% of variance in torque,
16 enabling more precise estimations. A slightly higher prediction of EMG amplitude
17 from thickness change has been reported for the lumbar multifidus, r^2 0.62 (Kiesel et
18 al., 2007). A higher prediction has been found for biceps brachii, obliquus internus,
19 brachialis and transversus abdominis, r^2 0.75-0.9 (Hodges et al., 2003, McMeeken et
20 al., 2004). No prediction has been documented for internal and external oblique, r^2
21 0.02 and 0.05, respectively (Brown and McGill, 2010). The MDC is an indicator of
22 clinical utility of estimating activity levels from thickness measurements. The MDC
23 was 20.8% of total gluteus medius thickening in 80% MVIC, low activity levels cannot
24 be distinguished from measurement error. The high MDC indicates that the error of

1 US thickness measurements was a substantial part of prediction inaccuracy.
2 Measurement accuracy was examined by intra-tester reliability and by intra-subject
3 variation of the measurements of relaxed muscle thickness (Tables 3 a and b).
4 Measurement variation was in the range reported by Mannion et al. (2008) and by
5 Critchley and Coutts (2002).

6 Gluteus minimus thickness stayed constant or decreased by 8% during high
7 level activity, providing no base for estimating torque production. The slightly differing
8 results between the surface and the fwEMG studies may result from the slightly
9 different measurement locations.

10

11 *Different thickening behaviour of synergistic muscles*

12 Differences in the thickening behaviour of superficial and deep synergistic
13 muscles have been reported. The superficial obliquus externus demonstrated an
14 unpredictable and task dependent thickening behaviour (John and Beith, 2007)
15 whereas the deeper obliquus internus and transversus abdominis muscles thickened
16 in a linear (McMeeken et al., 2004) or curvilinear manner (Hodges et al., 2003).
17 Superficial gastrocnemius medialis kept constant thickness while gastrocnemius
18 lateralis and deep soleus thickened with isometric activity (Managaris et al., 1998).

19 Muscle compression by adjacent synergists has been discussed to cause
20 constant or reduced muscle thickness during activation (Hodges 2005, Delaney et al.,
21 2010). It may be suggested that gluteus minimus cannot thicken due to pressure from
22 gluteus medius. Then, in slow contractions, initial thickening of gluteus minimus may
23 be detectible before pressure from gluteus medius has been built up. Figure 5 a, b
24 present representative slow activations in 40% and 80% MVIC without observable

1 thickening of gluteus minimus during isometric contractions, neither in the initial nor in
2 a later phase. Muscle architecture studies suggest further inferences on diverse
3 thickening behaviour (Narici et al., 1996, Herbert and Gandevia, 1995). The change
4 of muscle thickness during activity is explained by the thickening of muscle fibres
5 during contraction (Boyett et al., 1991). In parallel muscles, the increase of a fibre's
6 cross-section results in an increase of muscle thickness. In pennate muscles, muscle
7 thickness has been modelled as a function of fascicle length (FL), pennation angle
8 (θ) and the angle γ between lower and upper fascia, assuming straight fascicles in a
9 two-dimensional model:

$$10 \quad \text{Muscle thickness} = \text{Fascicle length} * \sin (180^\circ - (\gamma + 180^\circ - \theta)) / \sin (\gamma + 90^\circ)$$

11 (Blazevich et al., 2006), which can be simplified to:

$$12 \quad \text{Muscle thickness} = \text{Fascicle length} * \sin \theta$$

13 in the case of parallel muscle fascias.

14 If fascicle shortening and the increase in pennation angle compensate for
15 each other, muscle thickness remains constant during activity, as documented for the
16 medial gastrocnemius (Narici et al., 1996) and as assumed in classical models of
17 dynamic muscle architecture (Otten, 1988). If the effect of pennation increase
18 exceeds fascicle shortening, the muscle thickens during activity, e.g. soleus
19 (Managaris et al., 1998). The relationship between fascicle shortening and increase
20 in pennation angle appears to be variable between muscles. If a muscle is thinning,
21 fibre shortening may exceed the effect of pennation increase.

22 *[Insert Figure 6]*

23 Gluteus minimus is a unipennate muscle (Gottschalk et al., 1989) (Fig. 6). In
24 isometric gluteus minimus activity, the direction of fibre pull is oblique towards the

1 iliac bone, counteracted by the limits of tendon/fascia elasticity and by the elasticity of
2 the connective tissue network. This architectural constellation together with the notion
3 that fibre shortening may counterbalance or exceed thickening is a possible
4 explanation for constant or even reduced muscle thickness during activity (Fig. 5). A
5 scanning plane that provided full view on gluteus medius and minimus fascicles could
6 not be identified. Therefore data were not appropriate for fascicle measurements
7 (Bénard et al., 2009).

8

9 *Limitations*

10 The study results are limited to the measurement locations (Fig.2) which do
11 not reflect posterior muscle parts, and to isometric, sustained muscle activity.

12 Muscles may thicken due to increased activity or due to length changes (Shi et al.,
13 2009). Clinical tasks which include also dynamic activity will probably yield different
14 results.

15 FwEMG represents only a very small muscle volume including few motor units. It is
16 difficult to control whether exactly the same muscle section is scanned by US. While
17 differences in the probed muscle volume may account for inconsistencies in lower
18 torque levels, they should not affect the agreement in high levels of torque.

19 Estimation of activity levels from muscle thickening requires the same part of the
20 muscle being measured during relaxation and activation. Gluteus medius thickness is
21 not uniform (Grimaldi et al., 2009, Fig. 1). Muscle motion during activation may bring
22 a gluteus medius section of anatomically different thickness into the US field of view.

23 In our studies, motion within the frontal/coronal body plane could be controlled in the
24 longitudinal scanning plane. A retrospective control of transverse muscle motion was

1 possible for the main study, in which transversely scanned data had also been
2 collected. The transverse US recordings suggested regular gluteus medius motion
3 out of the longitudinal scanning plane during isometric hip abduction. Muscle motion
4 out of the scanning plane may have contributed to reduced prediction accuracy. In
5 order to measure thickness change in muscles of non-uniform thickness, muscle
6 motion needs to be controlled in both scanning planes and a measurement location
7 on which anatomical thickness stays constant with activity must be determined. To
8 the authors' knowledge, this methodological consideration for muscle thickness
9 measurements has not been mentioned in the literature. Gluteus minimus thickness
10 is relatively uniform, and only little transverse motion was recognized.

11 A further limitation refers to the power of the fwEMG analysis. While the power
12 to detect gluteus medius thickness change in the main study was 0.93, the small
13 sample of the fwEMG study provided a power of 0.74 to detect gluteus minimus
14 thickness change. The statement of gluteus minimus thinning in the anterior muscle
15 warrants further examination.

16

17 **Conclusions**

18 The precision of estimating gluteus medius activity level by US measured
19 thickness change was lower than using sEMG. Gluteus minimus isometric activity
20 level could not be estimated from thickness change. Other US measurements than
21 muscle thickness should be considered for assessing gluteus minimus isometric
22 activity.

23

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22

1 **Tables**

2 **Table 1**

3 Data inclusion, included data bold; Gmed, gluteus medius; Gmin, gluteus minimus

	<i>Main study, 165 trials, n=15</i>		<i>fwEMG study, 66 trials, n=6</i>	
Torque prediction from muscle thickening	<i>Gmed thickness not measurable in 2 trials, =163 trials (98.8)</i>	<i>Gmin thickness not measurable in 1 subject + 5 trials, =149 trials (90.3%)</i>	Ok, =66 trials (100%)	Gmin thickness not measurable in 1 trial, =65 trials (98.5%)
EMG amplitude prediction from muscle thickening	<i>Gmed EMG artefactual in 1 subject + 2 trials, =150 trials (90.9%)</i>	<i>n.a.</i>	Gmed EMG artefactual in 2 trials, =63 trials (95.5%)	Gmin EMG artefactual in 1 trial, =65 trials (98.5%)

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7 **Table 2**

8 Intra-tester reliability of M-mode thickness measurements of relaxed and activated Gmed and
9 Gmin muscle thickness; n=number of trials

	Gmed main study, n=87	Gmed fwEMG study, n=42	Gmin main study, n=87	Gmin fwEMG study, n=42
Relaxed: <i>ICC_{3,1}, (C.I.)</i>	0.957, (0.935-0.986)	0.927, (0.868- 0.960)	0.933, (0.896- 0.957)	0.890, (0.804- 0.939)
Diff: mean (SD); MDC, mm	-0.1 (1.0); 2.0	-0.1 (0.6); 1.3	-0.0 (1.4); 2.7	0.2 (0.6); 1.2
Activated: <i>ICC_{3,1},(C.I.)</i>	0.962, (0.943- 0.975)	0.950, (0.911- 0.972)	0.884, (0.828-0.923)	0.857, (0.751- 0.920)
Diff: mean (SD); MDC, mm	0.0 (1.0), 2.0	0.3 (1.0), 2.0	0.2 (0.8), 1.6	0.3 (0.9), 1.8

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1 **Table 3a)**

2 Main study, Gmed and Gmin thickness change with 80% activation per subject, intra-subject variation
3 of measurements of relaxed muscle thickness, mm.

subject	Relaxed Gmed thickness	Gmed thickness 80% MVIC	Thickness change	Relaxed Gmed thickness variation, SD, MDC	Relaxed Gmin thickness	Gmin thickness 80% MVIC	Thickness change	Relaxed Gmin thickness variation, SD, MDC
10	22.81	27.84	5.03	0.70, 1.37	15.74	14.57	-1.17	0.19, 0.37
11	32.43	34.08	1.65	0.37, 0.72	15.56	16.17	0.61	0.21, 0.42
14	21.91	25.05	3.14	0.41, 0.80	11.32	13.16	1.84	0.42, 0.82
18	29.19	37.47	8.28	0.69, 1.35	17.62	17.44	-0.18	0.49, 0.96
29	21.49	23.66	2.17	0.70, 1.37	17.33	17.12	-0.21	0.19, 0.37
37	21.25	29.33	8.08	0.76, 1.50	15.80	16.58	0.78	0.29, 0.57
43	22.52	27.04	4.52	0.37, 0.72	24.42	28.59	4.17	0.44, 0.86
49	25.98	34.75	8.77	0.56, 1.09	22.70	22.36	-0.34	0.65, 1.27
54	24.58	29.47	4.89	0.38, 0.75	21.17	21.35	0.18	0.50, 0.98
64	20.33	23.37	3.04	0.50, 0.98	17.26	14.54	-2.72	0.69, 1.36
71	22.34	31.39	9.05	0.44, 0.87	25.42	22.23	-3.19	0.41, 0.80
76	26.71	31.11	4.40	0.47, 0.93	20.43	20.51	0.08	0.20, 0.40
77	26.73	29.24	2.51	0.73, 1.44	19.39	19.43	0.04	0.39, 0.77
89	22.84	27.67	4.83	0.54, 1.05	22.62	23.08	0.46	0.71, 1.40
97	23.07	27.58	4.51	0.36, 0.70	19.81	16.44	-3.37	0.03, 0.07
av	24.28	29.27	4.99	0.53, 1.04	19.11	18.90	-0.20	0.39, 0.76

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5 **Table 3b)**

6 Fine-wire EMG study, Gmed and Gmin thickness change with maximal activation, intra-subject
7 variation of measurements of relaxed muscle thickness, mm.

subject	Relaxed Gmed thickness	Gmed thickness max activity	Thickness change	Relaxed Gmed thickness variation, SD, MDC	Relaxed Gmin thickness	Gmin thickness max activity	Thickness change	Relaxed Gmin thickness variation, SD, MDC
Fw3	26.25	29.49	3.25	0.35, 0.68	17.46	17.88	0.42	0.26, 0.50
FW10	21.81	30.45	8.64	0.33, 0.64	22.39	18.13	-4.26	0.37, 0.72
Fw11	20.71	18.36	-2.35	0.54, 1.06	19.40	18.00	-1.40	0.98, 1.91
Fw15	24.09	32.14	8.05	0.63, 1.23	21.10	18.95	-2.15	0.50, 0.97
Fw5	35.39	36.40	1.01	0.99, 1.93	19.01	18.18	-0.83	0.64, 1.25
Fw8	27.95	35.81	7.86	0.47, 0.92	19.24	17.75	-1.49	0.47, 0.93
av	26.03	30.44	4.41	0.55, 1.08	19.77	18.15	-1.62	0.53, 1.05

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1 Table 4a)

2 Main study: correlation (r), significance (p), determination coefficients (R^2) of the percentage of
 3 change of Gmed and Gmin thickness with torque.

subject	Gmed r	Gmed p	Gmed R^2 linear	Gmed R^2 exp.	Gmin r	Gmin p	Gmin R^2 linear	Gmin R^2 exp.
10	0.644*	0.033	0.414	0.419	0.147	0.665	0.022	0.026
11	0.654*	0.029	0.427	0.414	-0.081	0.813	0.007	0.003
14	0.939**	0.000	0.882	0.859	-0.269	0.423	0.072	0.092
18	0.924**	0.000	0.853	0.792	0.199	0.557	0.040	0.030
29	0.883**	0.000	0.779	0.728	0.040	0.912	0.002	0.003
37	0.852**	0.001	0.726	0.788	0.850**	0.001	0.723	0.725
43	0.751*	0.008	0.565	0.555	<i>Excluded, only four measurement points</i>			
49	0.768*	0.006	0.589	0.593	0.396	0.292	0.156	0.185
54	0.884*	0.002	0.782	0.708	-0.281	0.463	0.079	0.063
64	0.781*	0.005	0.610	0.625	-0.339	0.308	0.115	0.110
71	0.912**	0.000	0.832	0.862	0.370	0.293	0.137	0.098
76	0.612*	0.046	0.374	0.422	0.179	0.620	0.032	0.039
77	0.701*	0.016	0.491	0.522	0.014	0.968	0.000	0.001
89	0.880**	0.000	0.774	0.759	0.050	0.884	0.002	0.002
97	0.866**	0.001	0.750	0.748	-0.530	0.093	0.281	0.224

4 *significant at .05, ** significant at .001

5 Table 4b)

6 FwEMG study: correlation (r), significance (p), determination coefficients (R^2) of the percentage of
 7 change of Gmed and Gmin)thickness with torque.

subject	Gmed r	Gmed p	Gmed R^2 linear	Gmed R^2 exp.	Gmin r	Gmin p	Gmin R^2 linear	Gmin R^2 exp.
Fw3	0.580*	0.048	0.337	0.438	-0.673*	0.016	0.453	0.460
FW10	0.973**	0.000	0.947	0.886	-0.921**	0.000	0.825	0.812
Fw11	-0.805*	0.003	0.647	0.619	-0.519	0.102	0.269	0.249
Fw15	0.818*	0.002	0.669	0.648	-0.629*	0.051	0.395	0.438
Fw5	0.744*	0.009	0.554	0.475	-0.760*	0.007	0.578	0.539
Fw8	0.656*	0.028	0.430	0.509	-0.472	0.143	0.222	0.286

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1 **Captions to Illustrations**

2

3 Fig. 1. Isometric hip abduction recorded by dynamometry, US and surface EMG.

4 Fig. 2. US probes (white rectangles) and surface electrode (dotted circles) locations,
5 triangular shape: von Hofstetter's triangle; M-mode traces of sustained activity: a, main
6 study; b, fine-wire EMG study.

7 Fig. 3. Xyplot of the percentage of gluteus medius (Gmed) thickness change in 20% –
8 80%MVIC, including linear regression for each subject. Markers represent single trials per
9 subject, subjects differentiated by marker type.

10 Fig. 4. Xyplot of the percentage of gluteus minimus (Gmin) thickness change in 20% –
11 80%MVIC, including linear regression for each subject. Markers represent single trials per
12 subject, subjects differentiated by marker type.

13 Fig. 5a. Course of muscle thickness changes during a slow 40% MVIC activation (white force
14 trace), surface EMG study.

15 Fig. 6b. Course of muscle thickness changes during a slow 80% MVIC activation (white force
16 trace), surface EMG study.

17 Fig. 6. Unipennate arrangement of gluteus minimus fascicles and direction of pull during
18 activity (transparent arrow). Note that the fascicles are delineated only in part, an indication
19 that scanning was not in the fascicle plane and the image not appropriate for taking valid
20 fascicle measurements (Bénard et al., 2009).

21

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- 2 The authors acknowledge the loan of ultrasound equipment by Siemens
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Figure

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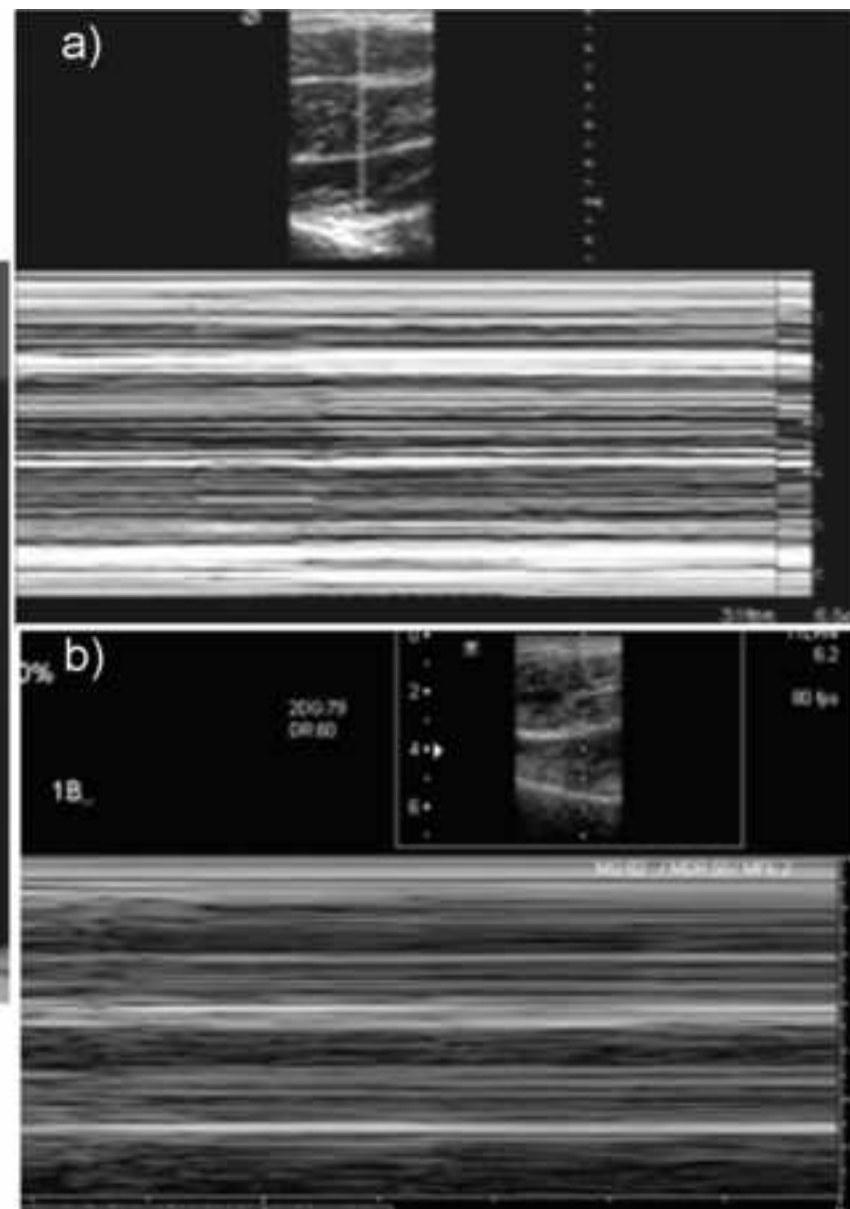
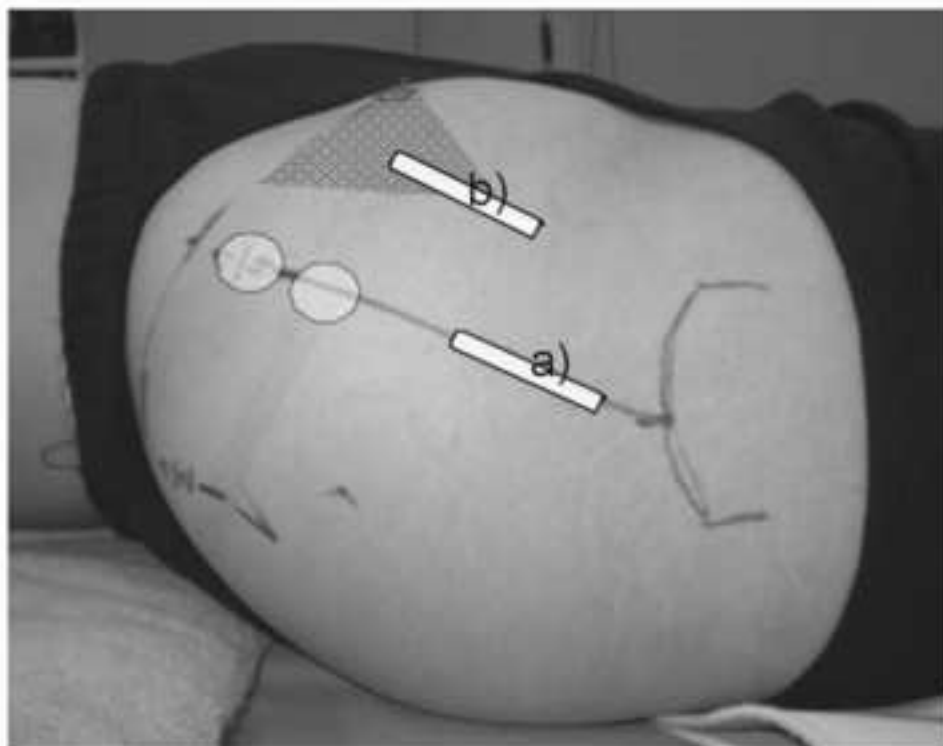


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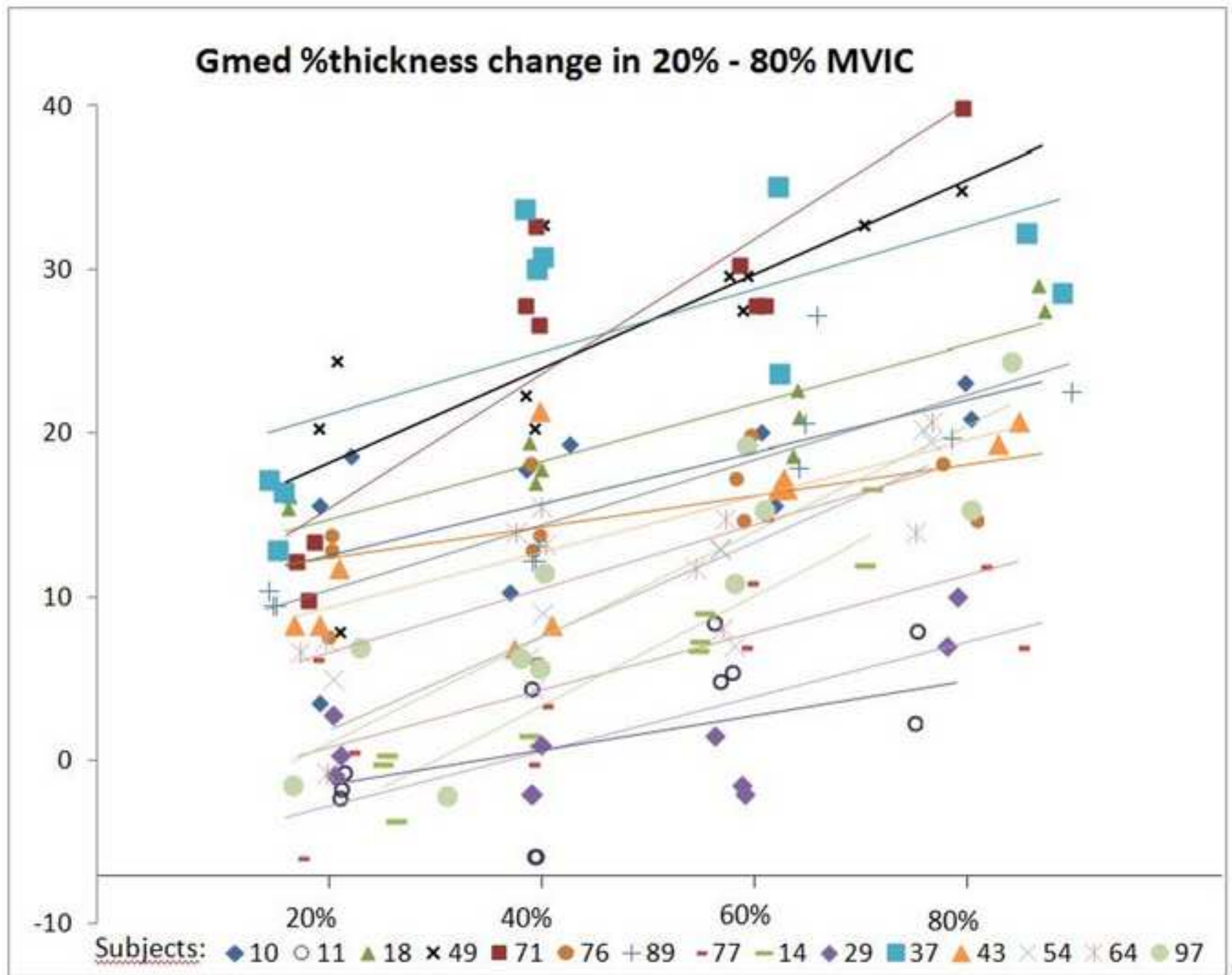
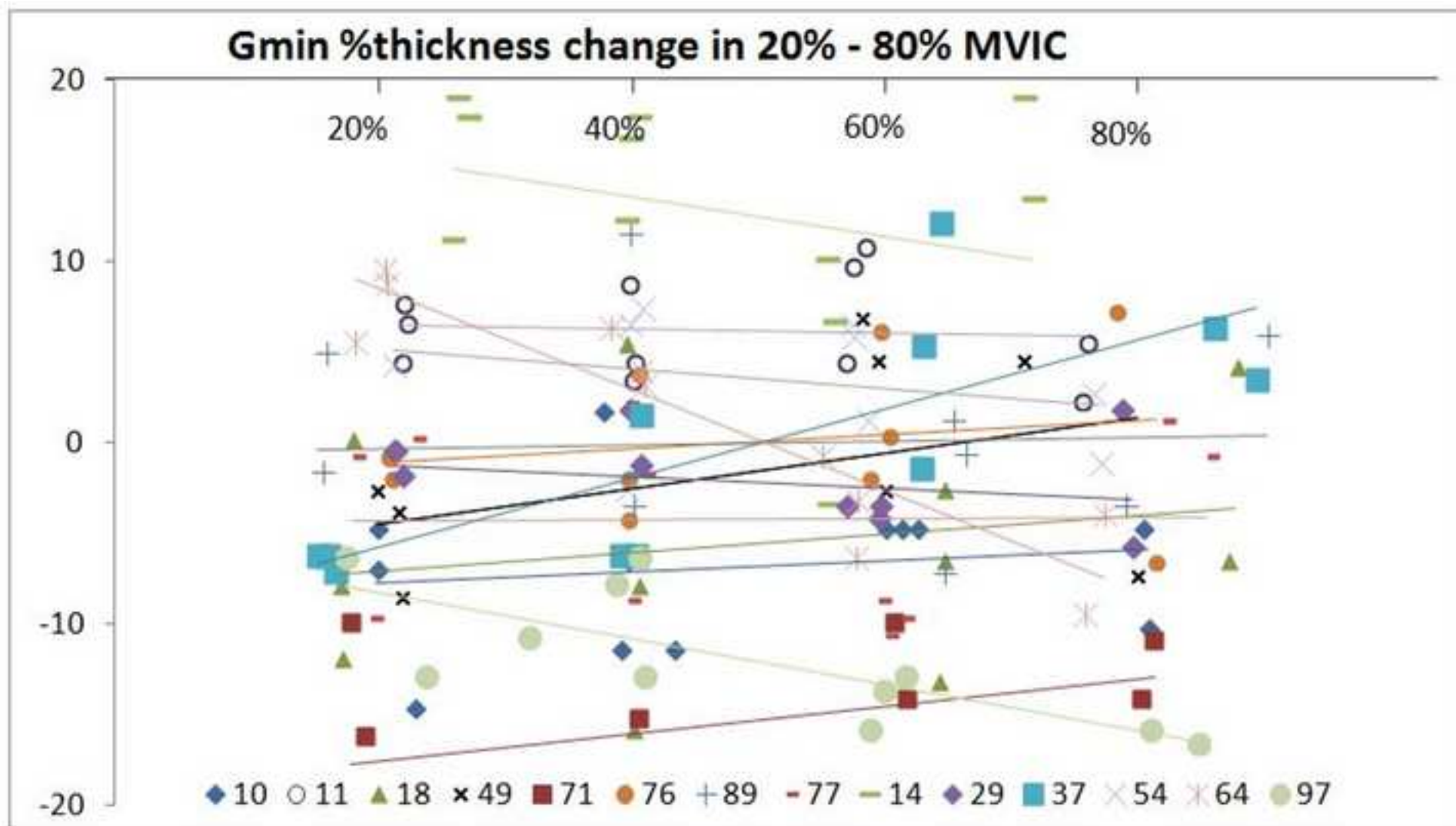
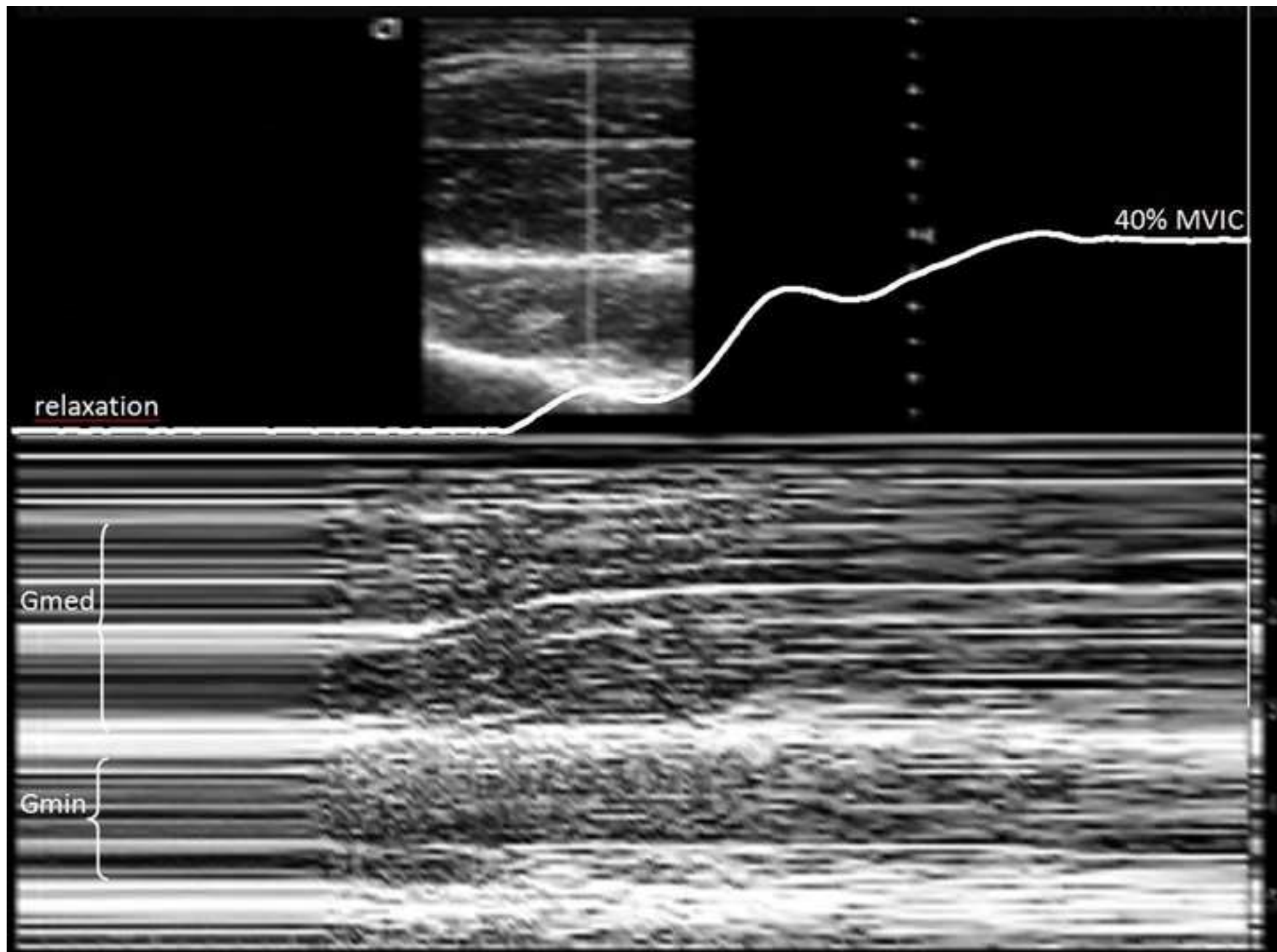


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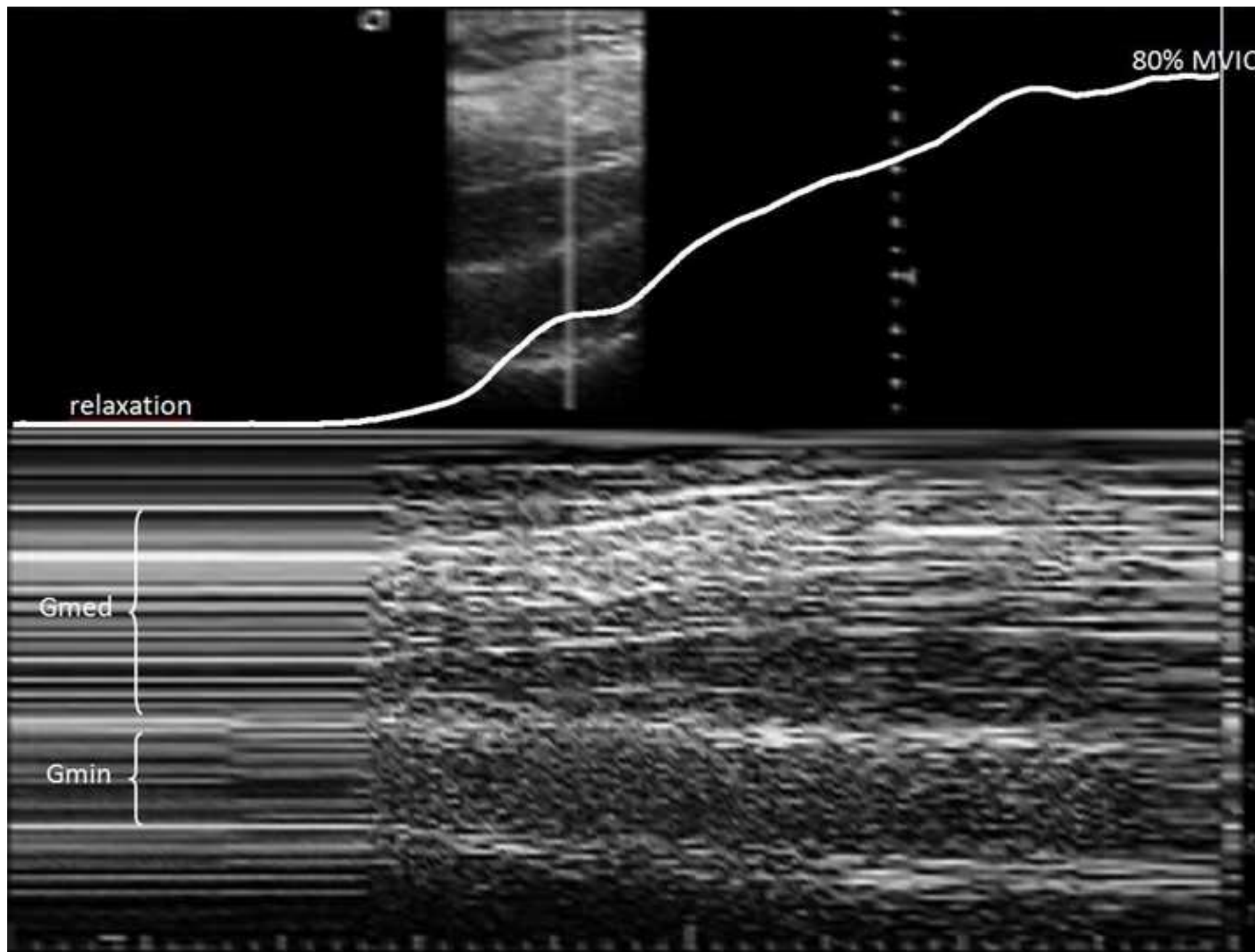
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