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Activation patterns of human abdominal muscles during walking: electrode positions make a difference

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Abstract

Purpose The study was intended to determine if different portions of abdominal muscles are characterized by accordingly differing activation patterns during walking. Further, the influence of walking speed and sex were considered as well. **Method** For this 53 healthy subjects of both sexes (26 females, 28.1 ± 10 years; 27 males, 26.8 ± 7.0 years) were enrolled in the study. They walked on a treadmill at speeds of 2 to 6 km/h. Surface EMG was taken from three abdominal muscles of both sides using two electrode locations per muscle: one at the recommended position and one at a systematically shifted position. Muscles studied were: rectus abdominis, internal oblique, and external oblique abdominal muscles. From the grand averaged amplitude curves mean amplitudes and Minimum to Maximum Range values were derived and compared between the respective positions. **Results** According to the ANOVA, position systematically influenced mean amplitude and Range levels for RA and EO, but not for IO. The mentioned differences were all in favor for the shifted positions. Significant differences between amplitude curves occurred in all muscles. These differences were more pronounced in males for RA and EO and decreased with increasing walking speed. Females in contrast to males showed positive and negative differences of the shifted positions within muscles whereas in males the observed differences remained either constantly positive for RA and EO or negative for IO. The observed differences mostly seem to augment situational stability during gait, indicating a finely tuned and situational adequate shift between mobilizing and stabilizing functions. **Conclusion** Therefore, a general assignment of abdominal muscles to only stabilizing or mobilizing functions seems to be inappropriate.

Keywords
Human; abdominal muscles; Surface EMG; activation pattern; electrode position

1 Introduction

As is well known any directional action of muscles is primarily determined by their anatomically defined origins and insertions (1, 2). Also, muscles are functionally driven, consequently resulting in functionally based, stochastic activation patterns (3). Based on these premises it is logically consistent to expect spatially varying functions if muscles do not only have single spot insertions, but insert across larger regions. That should lead to different activation characteristics of the respective muscles as well.

If spatial differences in muscle activation have to be analyzed several more subjective and also objective methods are available. Spatially differing activation patterns within or between muscles can be monitored by eye (4), palpation (5), through measures of muscle tone/pressure (6, 7), volume changes (8), regional analyses of temperature production (9), multiple inserted fine wire or needle EMG measurements (10), but, best suited, because of its non-invasive characteristic by Surface EMG (SEMG) (11). Especially the mentioned stochastic and spatially variable nature of muscle activation led to the development of multi-electrode SEMG, so called mapping techniques (12-14). Anyhow, these techniques although they provide promising results are still mainly applied with respect to specific scientific investigations and are therefore far away from routine practical application (15-21). With respect to routine SEMG application still only one single electrode position is recommended for almost all muscles (22, 23). Only if muscles are known to have separate single origins that are represented by differently named muscle parts also separate electrode positions are recommended (22, 23).

With respect to abdominal muscles, to only mention one major location, the discrepancy between recommended single electrode positions and the expectation of spatially different activation characteristics is obvious. So the question arises if these muscles should be investigated with respect to their anatomical variability or do they act as one complete unit. This interferes with the accepted classification of trunk muscles with respect to specific mobilizing and/or stabilizing function (24). Previous studies could already prove the influence of electrode position on SEMG amplitudes of trunk muscles (25, 26).

Therefore, the actual study was intended to specifically determine if different portions of abdominal muscles are also activated differently and further, if these activation patterns can be specifically characterized with respect to differences in mobilizing or stabilizing demands.

2 Methods

For this cross-sectional study 53 healthy age matched subjects of both sexes were recruited. Written informed consent was obtained from all subjects. Detailed information about the study purpose and procedure was provided. The study was approved by the ethics committee of the Jena University Hospital (3002-12/10). All subjects were clinically examined and briefly interviewed about their medical history. Exclusion criteria were relevant orthopedic and neurologic disorders and actual back pain. The subjects were informed about the investigation procedure and were asked to wear their own comfortable shoes. Selected anthropometric characteristics are given in Table 1.

2.1 Investigation procedure

After instrumentation (see below) subjects were asked to walk on a treadmill (TM). Since we expected to have mostly naïve subjects with respect to TM, all subjects were given adequate time to familiarize with the TM (27). Achievement of a normal gait pattern had to be in concordance with the subject's personal rating of comfortable walking and the investigator’s observation of a normal gait pattern: walking without holding onto the TM handrails, normal arm swing, stride frequency, body posture, and straightforward line of vision. After successful habituation, subjects walked for a minimum of 30 complete strides at walking speeds of 2 km/h to 6 km/h (resolution: 1 km/h). With this the required number of strides for reliable measurements was exceeded by far (28). Walking speeds were individually randomized to account for possible order effects and to prevent fatigue.

2.2 SEMG data collection and analysis

A common bipolar SEMG montage utilizing an inter-electrode distance of 2.5 cm was applied for measurement of three abdominal muscles of both sides: rectus abdominis (RA), internal oblique (IO), and external oblique (EO) abdominal muscles. For every abdominal muscle the recommended electrode position (22, 29) was expanded by an additional position, referred to as the 'shifted position' (Figure 1). The respective positions are detailed in Table 2. To minimize variances due to differences in electrode positioning all electrode positions were marked by the same well experienced examiner (C.A.). The respective positions were gently cleaned with abrasive paste (Epicont, GE Medical Systems) and shaved if appropriate. Additionally, cardiac activity was also detected by an additional bipolar channel along the heart axis. To exactly determine heel strikes, pressure sensors (FS402, Interlink Electronics) were applied below both heels.

All analog signals were captured (disposable electrodes, H93SG, Covidien) and amplified (gain 1000, -3 dB at 5 Hz and 700 Hz, DeMeTec), analog-to-digital converted (Tower of Measurement - ToM; 2048 samples/s, amplitude resolution: 24 bit at ± 5 V, anti-aliasing filter at 1024 Hz, DeMeTec), and stored on hard disk (ATISArec, GJB) for subsequent off-line analysis.

The captured SEMG data were band-pass filtered between 20 Hz and 400 Hz. To account for interferences from the electrical current supply, a 50 Hz notch filter was applied. Only steady state conditions were further used for analysis. This was obtained by a stepwise procedure, that i) excluded all strides deviating more than 10% from the median of all respective strides (based on the assumption of a physiological stride to stride variability of < 10% (30, 31)) and ii) by visually checking the amplitude curves of all remaining time normalized strides (see below) and all channels and excluding strides that deviated more than two SD from the mean.

All eligible strides were quantified as root mean square (rms) values and smoothed using a moving rectangular time window of 50 ms (overlap 49.5 ms). All valid strides were time-normalized with a time resolution of 0.5% resulting in 201 data points per stride. The resulting curves were further individually averaged for each electrode position, side, and walking speed.

These grand averaged amplitude curves were used to calculate mean amplitudes (i.e., average values over a complete normalized stride; time-independent parameter). Further, another time-independent parameter, the Range, was calculated that is the Minimum to Maximum Span of the grand averages amplitude curves during the complete stride, expressed as relative value according to the respective mean value. All mentioned calculations were performed using custom-made MATLAB scripts (The Mathworks).

2.3 Statistics

At first a repeated measures ANOVA (SPSS Statistics 24, IBM) with the main factors speed (2-6 km/h: 5 classes), position (recommended, shifted: 2 classes), and side (left, right: 2 classes) was performed separately for every muscle with sex serving as the between subject variable. This was done for the time-independent variables mean amplitude and Range.

To assess statistical differences between the grand averaged curves of the two walking conditions, paired t-tests were performed including Bonferroni-Holm corrections for multiple testing in order to avoid the accumulation of a type I statistical error (mainly due to the high number of time points; (32)). To simplify data display, in the results section in addition to a presentation of the grand averaged rms curves at the recommended positions relative differences of the shifted position will be shown that were referenced to the recommended position. Therefore, positive values indicate higher values for the shifted position.

3 Results

The grand averaged amplitude curves at the recommended positions are provided in Figure 2.

3.1 ANOVA Results

The ANOVA analysis of the mean RMS values revealed significant main effects of speed for all muscles. Position showed a significant main effect for RA and EO, whereas sex showed a systematic main effect for IO. Several interferences between the main factors could be observed (see Table 3 for details). For the Range this picture was virtually replied with an additional main effect of side for RA and IO.

3.2 Rectus abdominis muscle

Mean amplitude levels were always significantly higher for the caudally shifted position (Figure 3). The Min to Max Range tended to be elevated for the shifted position as well, but reached significant levels only for the slow walking speeds (Figure 4).

The differences of the grand averaged amplitude curves showed several significant differences that decreased with increasing speed and were further less obvious in the female subjects. As can be taken from Figure 5 (in accordance with the mean amplitude values) the shifted position showed significantly elevated amplitudes throughout the stance phase that reached differences up to 65% (2 km/h, males). These differences decreased with increasing speed and vanished at 6 km/h, except for remaining significances in the males just after ipsilateral heel strike and at contralateral heel strike.

3.3 Internal oblique muscle

In contrast to the RA, mean amplitudes for the IO did not show any systematic differences between the recommended and the shifted positions (Figure 3). The same accounts for the Range (Figure 4).

Differences in amplitude curves due to position shift became evident with increased walking speed, reaching significance in the males in late stance phase (up to 30% at 6 km/h, Figure 5). Observed differences were more pronounced in male subjects who always showed lower amplitudes for shifted positions. In the females the differences fluctuated between elevated (early to mid-stance, swing) and slightly lowered (late stance, contralateral heel strike) amplitudes at the shifted position that never reached significance.

3.4 External oblique muscle

The greatest electrode position effects were found in EO. Independent of the walking speed mean amplitudes and Range values were always significantly elevated in both sexes at the shifted position (Figures 3 & 4).

With such elevated differences in mind we expected to see permanently positive values in the difference plots of the amplitude curves, but this was not the case. Although the main deviation strongly pointed towards increased values for the shifted position this occurred mainly at slow to normal walking speeds and was more pronounced in the males (up to 110% increase, Figure 7). Starting at normal walking speed, at contralateral heel strike the amplitudes at the shifted position were lower. This was now most pronounced in the female subjects and could be significantly proven (up to 20% decrease at 4 & 6 km/h).

4 Discussion

The present investigation aimed at determining if the activation patterns for systematically shifted electrode positions of abdominal muscles were characterized by diverging activation patterns in comparison with the activation at the recommended positions. The shifted positions indeed showed different patterns that were further subject to muscle and sex. Saying this, no generalizable effect could be proven, requiring separate interpretation per muscle.

4.1 Rectus abdominis muscle

Mean amplitudes of RA were constantly larger for the shifted positions and, at least for slow walking speed also showed slightly elevated Range values. The relative differences for males showed almost homogenously increased amplitude patterns that only slightly decreased with increasing speed. In contrast, females' relative differences were much less developed, were limited to the stance phase and clearly decreased with increasing speed. Based on the muscle systems' definition of mobilizing and stabilizing muscle function at first sight the shifted position shows an even more pronounced mobilizing characteristic, because not only the amplitude levels increased but also the Min to Max Range (24). Since the Range is calculated as a relative value it is not influenced by amplitude level. Anyhow this behavior seems to be limited to slow walking speeds. At normal to fast walking speeds the principal activation characteristic was quite similar.

The observed amplitude differences have to be interpreted with caution (33), since no maximum voluntary contraction tests were performed. We found only a few studies that systematically investigated the two portions of the RA (34, 35). Unfortunately none of them performed investigations during walking. Escamilla and coworkers (34) performed a large set of gymnastic tasks that evoked both increased and decreased amplitudes of the lower in comparison with the upper RA portion. However, the authors showed a general tendency towards higher amplitudes for the lower portion when active flexion tasks were performed. In the present investigation largest increases for the shifted position were observed during stance phases, most obvious at slow walking speeds. The observed elevated amplitudes for RA shifted position (lower portion of RA) during stance therefore most probably account for an increased control of pelvic position and elevated stabilizing activity of the lower RA during slow walking stance phases. It appears that the lower portions of RA are able to swing between mobilizing and stabilizing functions.

4.2 Internal oblique muscle

Internal oblique muscles' mean amplitude and Range levels were not systematically influenced by position, and differed between sexes. In males the shifted position showed a continuously decreased amplitude level that became slightly more variable with increasing speed. For the men systematic differences occurred but were limited to terminal stance phase. In contrast, in females the shifted position showed amplitude elevation tendencies, though differences never deviated significantly from the recommended position. This amplitude elevation was most prominent at early to mid-stance and late swing phases. At these stride phases the countermovement of trunk vs hip reaches its maximal level and returns in the opposite direction (36). At the recommended position, absolute amplitude levels of IO are highest just at terminal swing, (37) especially in females (38), who in the current study showed increased activity of the upwards directed portions of IO. This increased amplitude of upper IO may relate to control of the reverting phase of the trunk hip countermovement indicating that IO acts as a global stabilizer muscle. To substantiate this claim a larger group size would be necessary. With the applied Bonferroni-Holm procedure the initial significance level of is very low (0.05/201 = 0.000248; (32)). With data from this study we already reached effect sizes of more than 1.0 indicating large effects, but significance was not reached.

4.3 External oblique muscle

Both mean amplitude levels and Range showed significantly elevated values independent from walking speed. Although, for the time-independent variables no systematic sex differences were identified the differences between the grand averaged curves showed clear sex-specific characteristics: males always showed elevated amplitudes for the shifted position that that reached significance. This was most pronounced during stance and swing phases; less so for early stance and swing especially with increasing walking speed. The females also showed elevated amplitudes of the shifted position during (early) stance, but contrary to the men showed significantly lowered amplitudes for the shifted position at contralateral heel strike at normal to fast walking speeds. The normal amplitude curve pattern of the EO at the recommended position (compare with Figure 2) can be described as almost continuous, but becoming more phasic with increasing walking speed (37). At the shifted position, especially during early stance and late swing, the amplitudes are considerably elevated. In other words, in preparation to and just after ipsilateral heel strike the shifted position shows mostly increased amplitudes. This could be due to increased stability demands. However during contralateral heel strike, at least in the females, the amplitudes for the shifted position were found to be lower. As can be taken from Figure 6 the differences at normal to fast walking speeds change rapidly, indicating abrupt amplitude changes between the recommended and shifted position. Because differences due to electrode positioning are so dynamic a more conclusive interpretation of the observed differences between the recommended and the shifted position of the EO cannot be provided yet. Most probably EO, at least for the shifted position, swings between augmented, attenuated stabilizing, and also mobilizing functions during stride.

5 Conclusion

Abdominal muscles are characterized by considerably varying SEMG activation patterns between and within muscles. The observed differences were nonuniform between muscles and sexes and were further subject to walking speed. Therefore, the presented results clearly indicate strongly situational activation patterns that put these muscles away from a strict muscle system related activation characteristic. Future diagnostics of trunk muscle function should best focus on these situational characteristics and at best should consider the functional diversity of the abdominal muscles with respect to differences between parts of these muscles. This could be applied to develop targeted therapeutic approaches to improve the outcome of back pain problems.

6 Acknowledgements

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7 Conflicts of Interest

All authors disclose any financial and personal relationship with other people or organizations that could inappropriately have influenced (bias) the work.

8 References

1. Kapandji IA. Funktionelle Anatomie der Gelenke. Obere Extremität - Untere Extremität - Rumpf und Wirbelsäule. 5 ed. Stuttgart: Georg Thieme Verlag; 2009.
2. Wappelhorst U, Kittelmann A, Röbbelen C. Lehr- und Arbeitsbuch Funktionelle Anatomie. 1 ed. München: Urban & Fischer; 2006.
3. McGill KC. Surface electromyogram signal modelling. Medical & Biological Engineering & Computing. 2004 Jul;42(4):446-54.
4. Janda V. Manuelle Muskelfunktionsdiagnostik: Elsevier, Urban&FischerVerlag; 2009.
5. Valerius KP, Frank A, Kolster BC, Hamilton C, Alejandre Lafont E, Kreutzer R. Das Muskelbuch. Anatomie Untersuchung Bewegung. 6 ed. Berlin: KVM - Der Medizinverlag; 2012.
6. Pruyn EC, Watsford ML, Murphy AJ. Validity and reliability of three methods of stiffness assessment. Journal of Sport and Health Science. 2016 12//;5(4):476-83.
7. Korhonen RK, Vain A, Vanninen E, Viir R, Jurvelin JS. Can mechanical myotonometry or electromyography be used for the prediction of intramuscular pressure? Physiological measurement. 2005 Dec;26(6):951-63. PubMed PMID: WOS:000234274700006.
8. Kim WS, Lee HD, Lim DH, Han JS, Shin KS, Han CS. Development of a muscle circumference sensor to estimate torque of the human elbow joint. Sensor Actuat a-Phys. 2014 Feb 1;208:95-103. PubMed PMID: WOS:000332443100011.
9. Ludwig N, Formenti D, Gargano M, Alberti G. Skin temperature evaluation by infrared thermography: Comparison of image analysis methods. Infrared Phys Techn. 2014 Jan;62:1-6. PubMed PMID: WOS:000331414200001.
10. Semciw AI, Pizzari T, Murley GS, Green RA. Gluteus medius: an intramuscular EMG investigation of anterior, middle and posterior segments during gait. J Electromyogr Kinesiol. 2013 Aug;23(4):858-64. PubMed PMID: 23587766.
11. Falla D, Farina D, Graven-Nielsen T. Spatial dependency of trapezius muscle activity during repetitive shoulder flexion. J Electromyogr Kinesiol. 2007 Jun;17(3):299-306. PubMed PMID: 16740396.
12. Falla D, Rainoldi A, Merletti R, Jull G. Spatio-temporal evaluation of neck muscle activation during postural perturbations in healthy subjects. J Electromyogr Kinesiol. 2004 2004/8;14(4):463-74.
13. Merletti R, Afsharipour B, Piervirgili G, editors. High Density Surface EMG Technology. Converging Clinical and Engineering Research on Neurorehabilitation; 2013; Toledo: Springer.
14. Stegeman DF, Zwarts MJ, Anders C, Hashimoto T. Multi-channel surface EMG in clinical neurophysiology. Supplements to Clinical neurophysiology. 2000;53:155-62. PubMed PMID: 12740990.
15. Staudenmann D, Kingma I, Daffertshofer A, Stegeman DF, van Dieen JH. Heterogeneity of muscle

activation in relation to force direction: a multi-channel surface electromyography study on the triceps surae muscle. J Electromyogr Kinesiol. 2009 Oct;19(5):882-95. Epub 2008/06/17.

16. Biedermann F, Schumann NP, Fischer MS, Scholle HC. Surface EMG-recordings using a miniaturised matrix electrode: a new technique for small animals. Journal of neuroscience methods. 2000;97(1):69-75.
17. Erler K, Neumann U, Bruckner L, Babisch J, Venbrocks R, Anders C, et al. Characterizing muscular coordination disorders in patients after the implantation of a total knee arthroplasty by means of emg mappping. Zeitschrift fur Orthopadie und ihre Grenzgebiete. 2000;138(3):197-203.
18. Fröbel A. Untersuchung funktioneller Charakteristika des M. quadriceps femoris in Abhängigkeit vom Kniegelenkswinkel bei Gesunden unter Nutzung des EMG-Mapping. Jena: FSU Jena; 2005.
19. Kleine BU, Schumann NP, Stegeman DF, Scholle HC. Surface EMG mapping of the human trapezius muscle: the topography of monopolar and bipolar surface EMG amplitude and spectrum parameters at varied forces and in fatigue. Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology. 2000 Apr;111(4):686-93.
20. Phillips LH, 2nd, Park TS. Electrophysiologic mapping of the segmental anatomy of the muscles of the lower extremity. Muscle Nerve. 1991 Dec;14(12):1213-8. PubMed PMID: 1766452.
21. Tucker K, Falla D, Graven-Nielsen T, Farina D. Electromyographic mapping of the erector spinae muscle with varying load and during sustained contraction. J Electromyogr Kinesiol. 2009 Jun;19(3):373-9. PubMed PMID: 18061480.
22. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol. 2000 Oct;10(5):361-74.
23. Hermens HJ, Freriks B, Merletti R, Stegeman DF, Blok J, Rau G, et al. European Recommendations for Surface ElectroMyoGraphy, results of the SENIAM project. Enschede: Roessingh Research and Development b.v.; 1999.
24. Comerford MJ, Mottram SL. Movement and stability dysfunction--contemporary developments. Manual therapy. 2001;6(1):15-26.
25. De Nooij R, Kallenberg LAC, Hermens HJ. Evaluating the effect of electrode location on surface EMG amplitude of the m. erector spinae p. longissimus dorsi. J Electromyogr Kinesiol. 2009;19(4):e257-e66.
26. Huebner A, Faenger B, Schenk P, Scholle HC, Anders C. Alteration of Surface EMG amplitude levels of five major trunk muscles by defined electrode location displacement. J Electromyogr Kinesiol. 2014 Dec 10. PubMed PMID: 25542505.
27. Van de Putte M, Hagemeister N, St-Onge N, Parent G, de Guise JA. Habituation to treadmill walking. Bio-medical materials and engineering.

2006;16(1):43-52. PubMed PMID: 16410643.

28. Hollman JH, Childs KB, McNeil ML, Mueller AC, Quilter CM, Youdas JW. Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals. Gait & posture. 2010 5//;32(1):23-8.
29. Ng JK, Kippers V, Richardson CA. Muscle fibre orientation of abdominal muscles and suggested surface EMG electrode positions. Electromyogr Clin Neurophysiol. 1998;38(1):51-8.
30. Danion F, Varraine E, Bonnard M, Pailhous J. Stride variability in human gait: the effect of stride frequency and stride length. Gait & posture. 2003 Aug;18(1):69-77.
31. Dubost V, Annweiler C, Aminian K, Najafi B, Herrmann FR, Beauchet O. Stride-to-stride variability while enumerating animal names among healthy young adults: Result of stride velocity or effect of attention-demanding task? Gait & posture. 2008 Jan;27(1):138-43. PubMed PMID: WOS:000252917200020.
32. Hemmelmann C, Horn M, Susse T, Vollandt R, Weiss S. New concepts of multiple tests and their use for evaluating high-dimensional EEG data. Journal of neuroscience methods. 2005 Mar 30;142(2):209-17. PubMed PMID: 15698661. Epub 2005/02/09.
33. Lehman GJ, McGill SM. The importance of normalization in the interpretation of surface electromyography: a proof of principle. Journal of manipulative and physiological therapeutics. 1999;22(7):444-6.
34. Escamilla RF, Lewis C, Bell D, Bramblet G, Daffron J, Lambert S, et al. Core Muscle Activation During Swiss Ball and Traditional Abdominal Exercises. J Orthop Sport Phys. 2010 May;40(5):265-76. PubMed PMID: WOS:000277583600003.
35. Stokes IA, Moffroid M, Rush S, Haugh LD. EMG to torque relationship in rectus abdominis muscle. Results with repeated testing. Spine. 1989 Aug;14(8):857-61. PubMed PMID: 2528820.
36. Perry J, Burnfield J, Cabico LM. Gait Analysis: Normal and Pathological Function. 2 ed. Thorofare: Slack Inc.; 2010.
37. Anders C, Wagner H, Puta C, Grassme R, Petrovitch A, Scholle HC. Trunk muscle activation patterns during walking at different speeds. J Electromyogr Kinesiol. 2007 Apr;17(2):245-52.
38. Anders C, Wagner H, Puta C, Grassme R, Scholle HC. Healthy humans use sex-specific co-ordination patterns of trunk muscles during gait. European journal of applied physiology. 2009;105(4):585-94.

9 Tables

Table 1: Study population

		Age [y]	Height [cm]	Weight [kg]	BMI [kg/m²]
female (n=26)	**Median**	24.5	168.0	60.4	22.2
	upp. Q.	3.3	2.8	9.2	2.5
	low. Q.	2.5	4.8	4.3	1.2
	Mean	28.1	167.6	64.1	22.7
	SD	10.0	6.0	10.3	2.7
T-Test		n.s.	<0.001	<0.001	n.s.
male (n=27)	**Median**	25.0	180.0	77.3	23.5
	upp. Q.	4.0	6.0	4.9	1.4
	low. Q.	2.0	6.0	7.3	1.7
	Mean	26.8	179.9	76.0	23.5
	SD	7.0	6.5	9.9	2.6

upp.Q.: upper Quartile; low.Q.: lower Quartile

Table 2: investigated muscles together with the electrode locations of the recommended and the shifted positions

Muscle	Position / Orientation
RA recommended	caudal electrode at navel height, 4 cm lateral from midline / vertical
RA shifted	cranial electrode 2 cm caudal from navel height, 4 cm lateral from midline / vertical
IO recommended	medial inguinal ligament, at ASIS height / horizontal
IO shifted	⅓ distance between ASIS to navel/ along line
EO recommended	cranial electrode directly below lowest point of the costal arch, ventral electrode at anterior axillary line / along line to contralateral pubic tubercle
EO shifted	½ distance costal arch to pelvic crest, ventral electrode at anterior axillary line / along line to ipsilateral ASIS

ASIS: anterior superior iliac spine

Table 3: Results of the ANOVA for mean amplitudes and Range. Significant p values appear in bold.

	Mean amplitudes		
	RA	IO	EO
Position	**0.001**	0.192	**<0.001**
Side	0.226	0.624	0.058
Speed	**<0.001**	**<0.001**	**<0.001**
Sex	0.402	**0.004**	0.620
Position * Sex	0.105	**0.012**[b sex]	**0.007**[b position]
Side * Sex	0.403	0.555	0.648
Speed * Sex	0.914	**0.048**[a]	0.653
Position * Side	**0.006**[b position]	**0.023**[c]	**0.001**[b position]
Position * Speed	0.992	0.411	0.537
Side * Speed	0.439	0.411	0.197

	Range		
	RA	IO	EO
Position	**0.007**	0.976	**<0.001**
Side	**0.018**	**0.010**	0.648
Speed	**<0.001**	**<0.001**	**<0.001**
Sex	0.258	**0.035**	0.056
Position * Sex	0.123	0.105	0.427
Side * Sex	0.609	0.497	**0.005**[c]
Speed * Sex	0.975	0.318	**0.025**[b side]
Position * Side	0.089	0.203	**0.025**[b position]
Position * Speed	0.326	0.321	**0.001**[a]
Side * Speed	**0.010**[a]	**<0.001**[b side]	0.591

[a]: ordinate interaction between main factors

[b]: hybrid interaction between main factors with the suffix stating the interpretable main factor

[c]: dysordinate Interaction between main factors

10 Figure captions

Figure 1: Aspect of a male subject with all electrode positions for the investigated abdominal muscles.

Figure 2: Grand averaged amplitude curves during walking at 2 to 6 km/h for RA, IO, and EO muscles obtained at the recommended electrode positions.

Figure 3: Mean amplitude values for the recommended and shifted electrode positions, pooled for sex. Asterisks indicate significant differences (RA: $p < 0.025$; EO: $p < 0.01$) between the respective positions.

Figure 4: Range values for the recommended and shifted electrode positions, pooled for sex. Asterisks indicate significant differences ($p < 0.01$) between the respective positions.

Figure 5: Relative differences between the grand averaged amplitude curves of the recommended vs the shifted positions for rectus abdominis muscle. Data appear separately for sexes (females: red, males: green) but were pooled for side. Note that significant differences between the positions appear as superimposed open circles ($p < 0.05$; including Bonferroni-Holm correction). If values at the shifted position exceeded those of the recommended position difference appear as positive values and vice versa.

Figure 6: Relative differences between the grand averaged amplitude curves of the recommended vs the shifted positions for internal oblique muscle. Data appear separately for sexes (females: red, males: green) but were pooled for side. Note that significant differences between the positions appear as superimposed open circles ($p < 0.05$; including Bonferroni-Holm correction). If values at the shifted position exceeded those of the recommended position differences appear as positive values and vice versa.

Figure 7: Relative differences between the grand averaged amplitude curves of the recommended vs the shifted positions for external oblique muscle. Date appear separately for sexes (females: red, males: green) but were pooled for side. Note that significant differences between the positions appear as superimposed open circles ($p < 0.05$; including Bonferroni-Holm correction). If values at the shifted position exceeded those of the recommended position difference appear as positive values and vice versa.

Figure 1

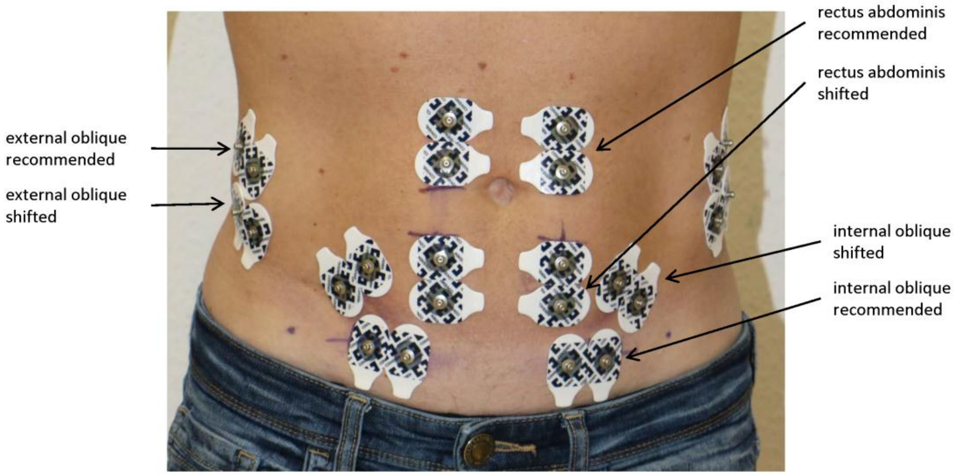

rectus abdominis recommended
rectus abdominis shifted
external oblique recommended
external oblique shifted
internal oblique shifted
internal oblique recommended

Figure 2

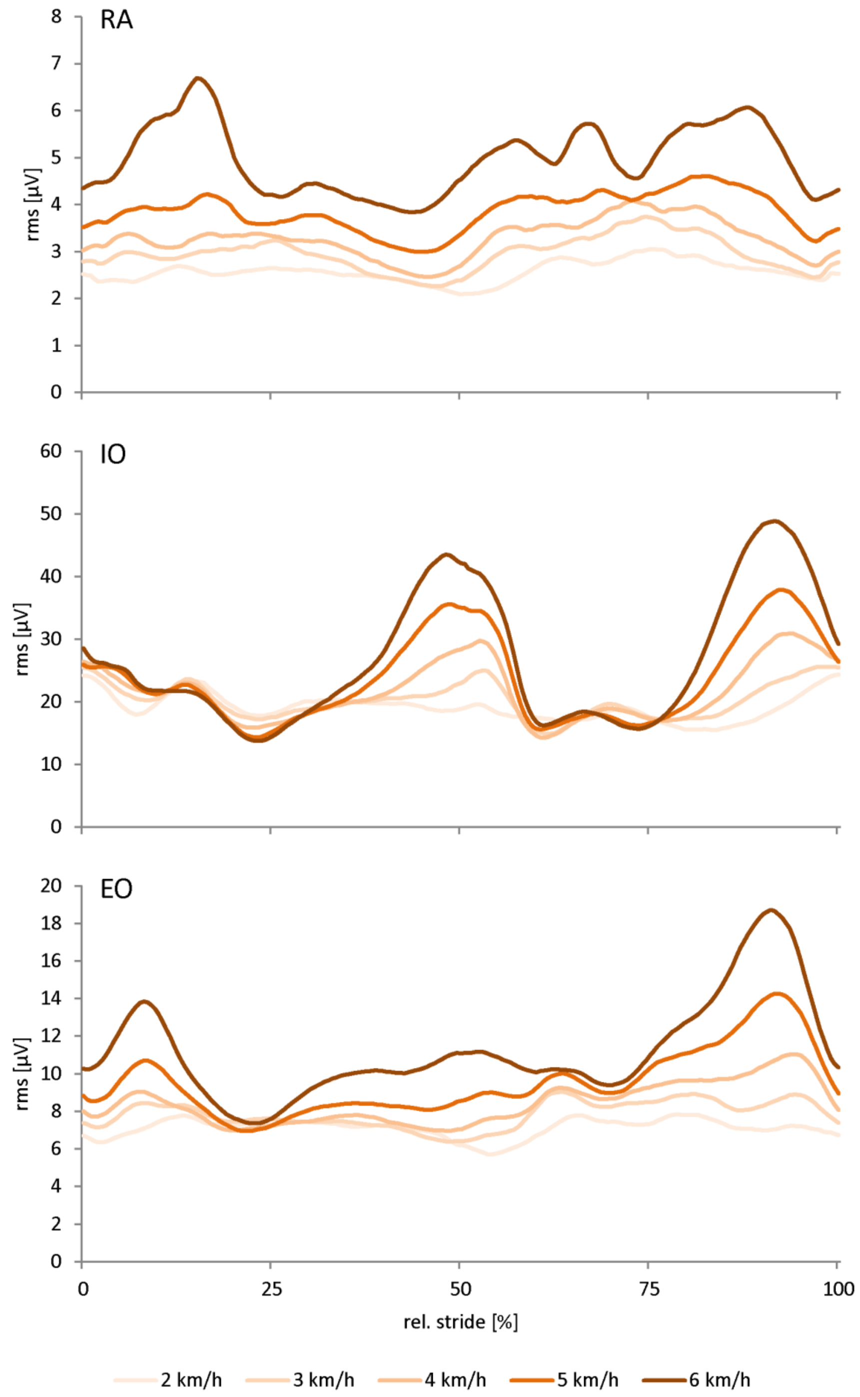

RA
IO
EO
rms [µV]
0
1
2
3
4
5
6
7
8
10
20
30
40
50
60
12
14
16
18
0
25
50
75
100
rel. stride [%]
2 km/h
3 km/h
4 km/h
5 km/h
6 km/h

Figure 3

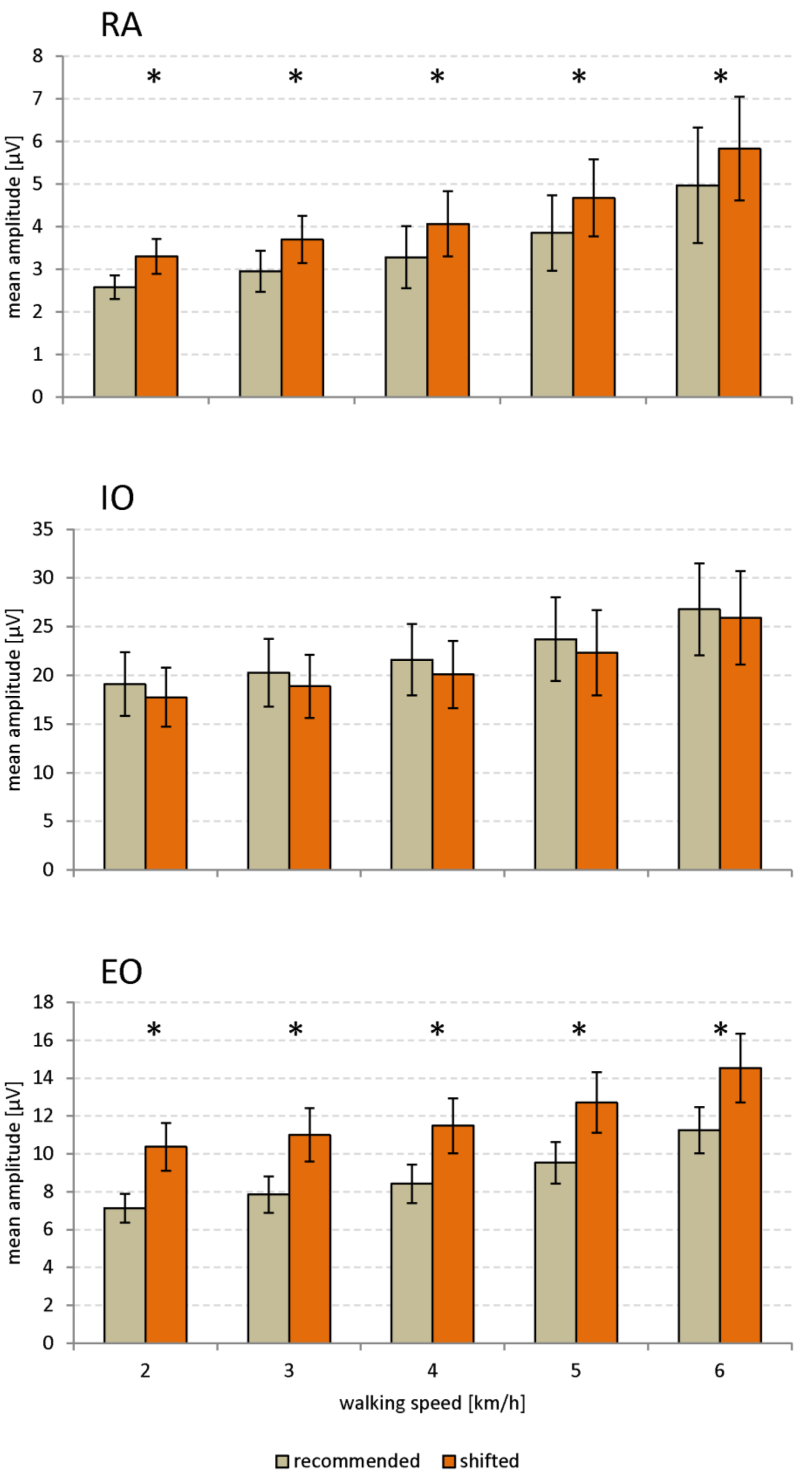

RA
mean amplitude [µV]
0
1
2
3
4
5
6
7
8
*
*
*
*
*
IO
mean amplitude [µV]
0
5
10
15
20
25
30
35
EO
mean amplitude [µV]
0
2
4
6
8
10
12
14
16
18
*
*
*
*
*
2
3
4
5
6
walking speed [km/h]
recommended
shifted

Figure 4

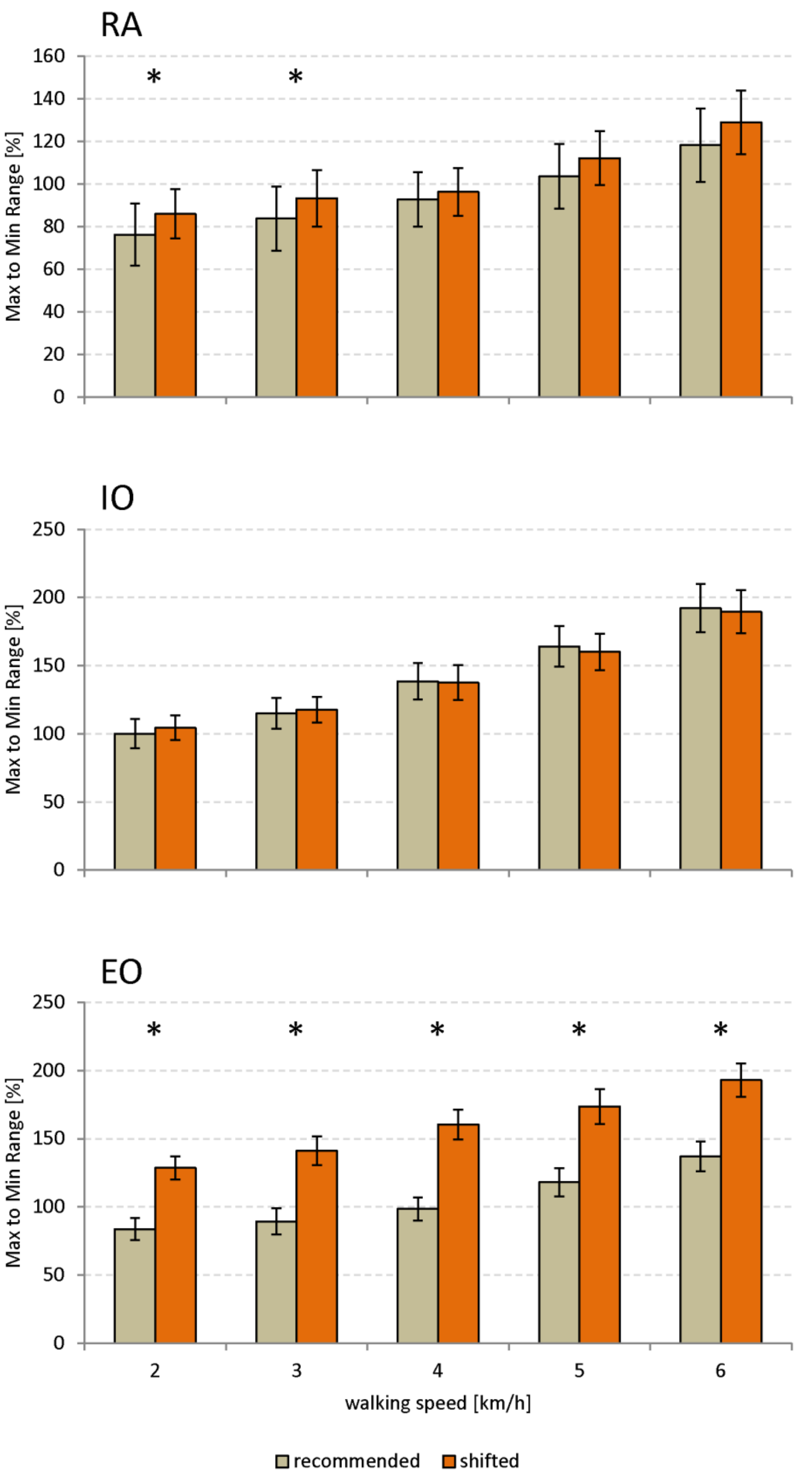

RA
160
140
120
100
80
60
40
20
0
Max to Min Range [%]
*
*
IO
250
200
150
100
50
0
Max to Min Range [%]
EO
250
200
150
100
50
0
Max to Min Range [%]
*
*
*
*
*
2
3
4
5
6
walking speed [km/h]
recommended
shifted

Figure 5

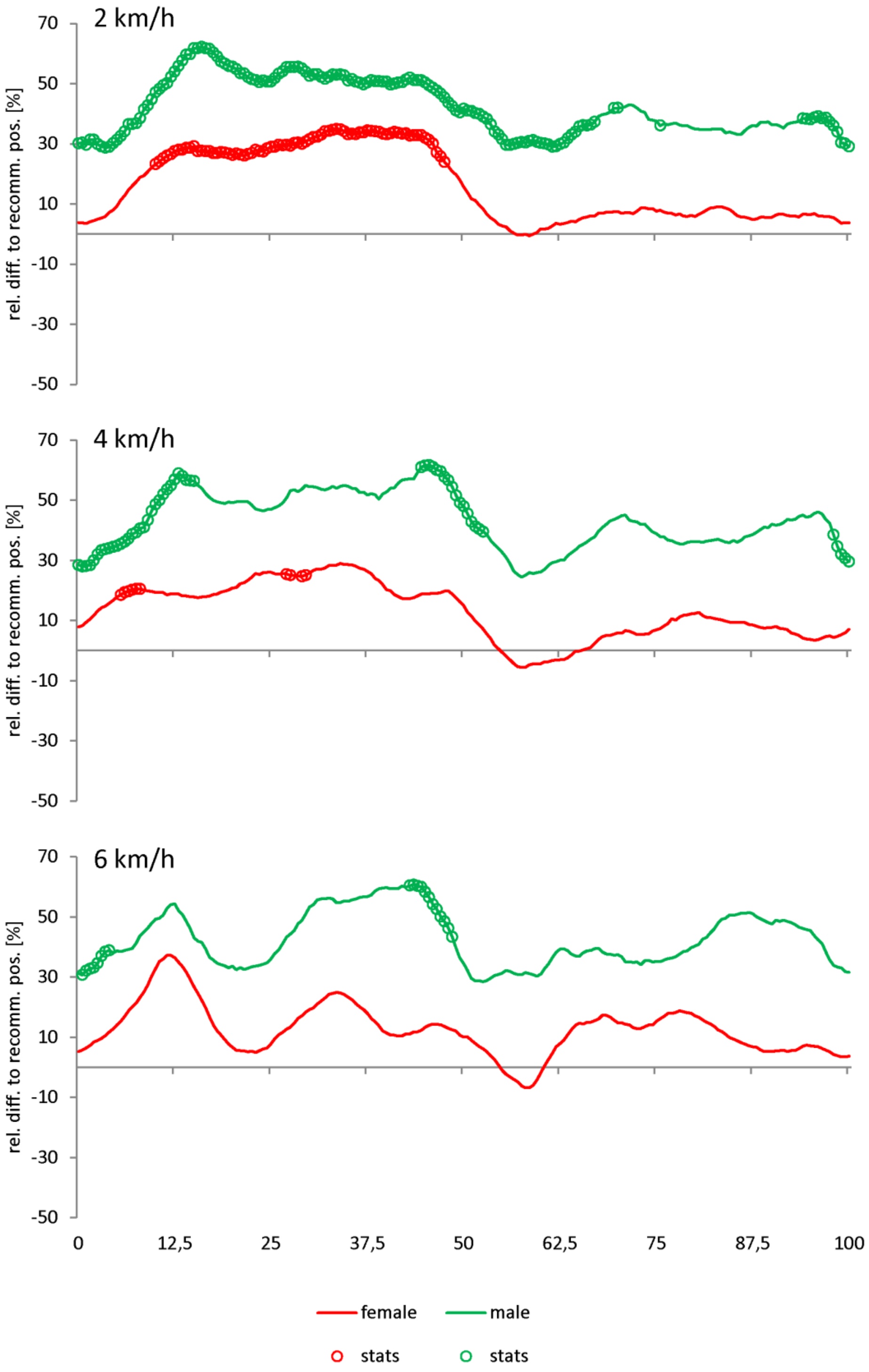

2 km/h
4 km/h
6 km/h
rel. diff. to recomm. pos. [%]
70
50
30
10
-10
-30
-50
0
12,5
25
37,5
50
62,5
75
87,5
100
female
male
stats
stats

Figure 6

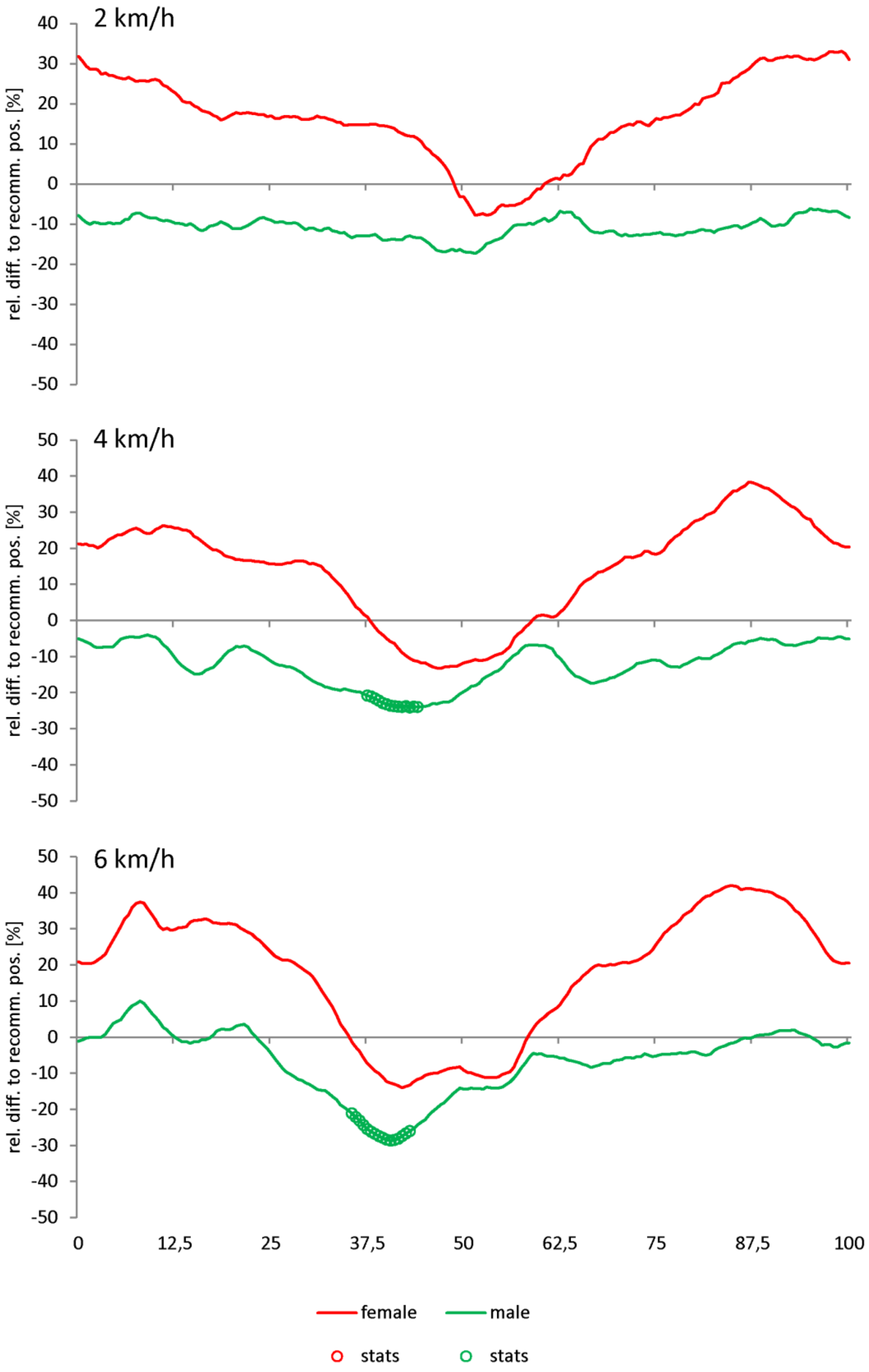
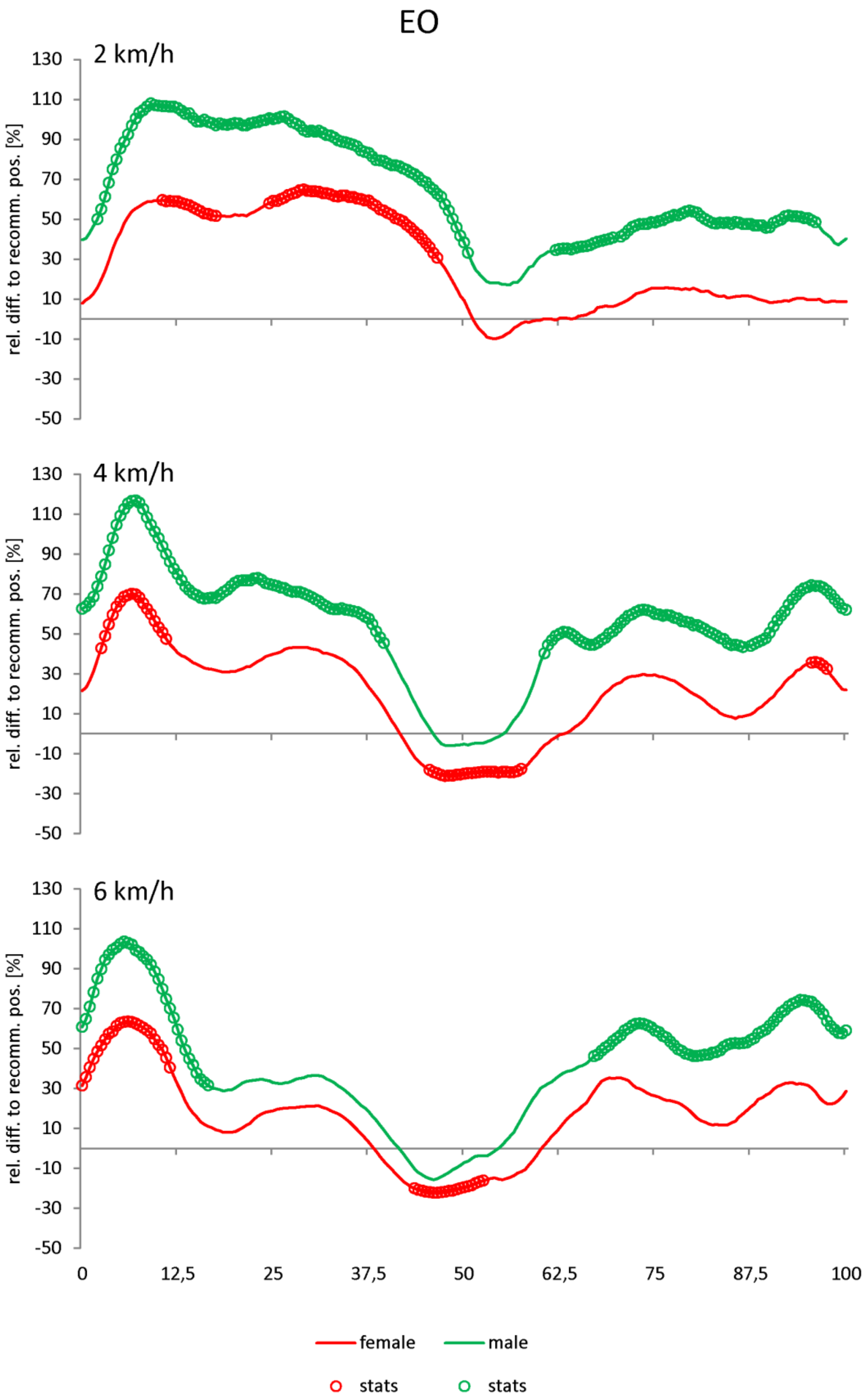

2 km/h
4 km/h
6 km/h
rel. diff. to recomm. pos. [%]
40
30
20
10
0
-10
-20
-30
-40
-50
0
12,5
25
37,5
50
62,5
75
87,5
100
female
male
stats
stats

Figure 7


EO
2 km/h
4 km/h
6 km/h
rel. diff. to recomm. pos. [%]
130
110
90
70
50
30
10
-10
-30
-50
0
12,5
25
37,5
50
62,5
75
87,5
100
female
male
stats
stats