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Surface electromyographic activity of trunk muscles during trunk control exercises for people after stroke; effect of a mobile and stable seat for rehabilitation

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Abstract

The aim of this study was to explore differences in trunk muscle activity on a stable and mobile seat for people after stroke and healthy participants. Trunk control exercises are known to have a beneficial effect on trunk control, balance, and mobility after stroke. The effect of such exercises could be enhanced by the use of a mobile seat to provide further training stimuli. However, little research on the musculoskeletal effects of trunk training on mobile seats has been carried out. On a stable and a mobile seat, thirteen people after stroke and fifteen healthy participants performed two selective trunk control exercises, which were lateral flexion initiated by the pelvis and the thorax. The maximal surface electromyography relative to static sitting of the muscles multifidus, erector spinae, and obliquus externus was recorded bilaterally. The effects of group, seat condition, trunk control exercise, and muscle side were investigated employing within-subject linear-mixed-models. Compared to the stable seat, the maximal muscle activity of people after stroke on the mobile seat was higher during the thorax-initiated exercise and lower during the pelvis-initiated exercise. Healthy participants showed opposite results with higher muscle activity on the mobile seat during the pelvis-initiated exercise. For trunk control training on a mobile seat with high muscle activation people after stroke should perform trunk control exercises initiated by the thorax, for training with lower muscle activity people after stroke should initiate selective trunk movements by the pelvis. The results can support the planning of progressive trunk control rehabilitation programs.

Introduction

The combined third-leading cause of death and disability in 2019 was stroke [1]. Therefore, it is still one of the leading causes of disease burden globally [2, 3]. While incidence rates are plateauing or decreasing slightly in richer countries, rates are increasing in poorer countries. Despite age-standardized rates of stroke having decreased over the last decade, the decline has been insufficient to compensate for world population ageing and growth. Hence, an increase is predicted for the coming years [1]. This increase additionally leads to more costs for rehabilitation as well as care if limited mobility remains, which is the case for 5 out of the 16 million people annually experiencing a first stroke around the globe [4].

Early post stroke, limited mobility can be caused by impaired trunk control [5]. Impaired trunk control is defined as the inability of the trunk muscles to maintain the body in an upright position, adjust weight-shift, or perform movements of the trunk, and encompasses an altered trunk position sense, poor trunk muscle strength, and balance difficulties [5, 6]. This inability to maintain the body in an upright position is also associated with impairments of functional outcomes such as balance, gait, arm, and hand function [6].

The initial severity of disability and extent of improvement observed within the first weeks post stroke were found to be substantial indicators of the functional outcome at six months [7–9]. It is also known that treatment intensity is important and neuroplasticity is greater early after stroke [10]. Additionally, the majority of motor recovery occurs during the first ten weeks after stroke. [7]. Therefore, early rehabilitation after stroke, especially of the trunk, is important. Because the impairment is higher early after stroke, selective trunk control exercises while sitting are suited best for trunk training during this rehabilitation stage. Trunk exercises, both on a stable or a mobile surface, have been shown to have a beneficial effect on trunk control, standing balance, mobility, dynamic sitting balance, and gait after stroke [11, 12]. This remains true even three months after cessation of regular training [11]. When the trunk control of people after stroke improves faster, gait and balance training can be started earlier and possibly lead to better recovery [13].

Particularly regarding standing and walking, selective trunk control, for example measured by the trunk impairment scale (TIS), is a predictor of the total functional outcome of rehabilitation [8, 9, 14]. Pelvic and lumbar control are prerequisites to proper movement control of the extremities which is needed in order to regain standing and walking abilities, or to adequately perform reaching [7, 15–17]. Another important predictor of motor and functional recovery after stroke is sitting balance which was identified in several studies [14, 18–20]. Training of sitting balance (while reaching beyond arm's length) yields a positive effect on gait and mobility related functions and abilities [21]. Because lateral sitting balance appears to be more affected by stroke than anteroposterior sitting balance, possibly due to the lack of foot support and the consequent greater dependence on trunk muscles during lateral shifting, training of lateral sitting balance is needed more urgently during rehabilitation [22]. Sitting balance could be improved with trunk control training [23].

Currently, training tools, which are designed for selective trunk control training and can be used early after stroke or for severely impaired stroke survivors, are scarce. A novel assistive therapy chair, incorporating a mobile seat, allows trunk training in a seated position early in the rehabilitation process in a safe environment, and at a potentially higher training intensity [24]. Karatas et al. (2004) found a positive relationship between trunk muscle strength and the Berg Balance Scale at discharge, which shows the importance of trunk muscle strength training during rehabilitation [25].

The specific effects of selective trunk exercises using a mobile or a stable seat on the musculoskeletal system, specifically muscle activity of the trunk musculature, are currently unknown.

Therefore, the aim of this exploratory study was two-folded. Primarily, the aim was to investigate whether the surface electromyographic activity (sEMG) of three trunk muscles during the performance of two selective lateral trunk control exercises is different on the mobile seat compared to the stable seat, in people after stroke (PAT) and in healthy participants (CON). The secondary aim was to find which of the factors seat condition, group, investigated side, or exercise type could predict trunk muscle activity.

Materials and methods

Participants

CON were recruited via mail from the university campus and wider public and PAT were recruited from the inpatient population of a rehabilitation center in Switzerland, both between September 2020 and March 2021. All participants were screened by verbal interview prior to enrolment based on preselected inclusion criteria (Table 1).

There were a total number of 28 participants of which 17 were male and 11 were female. Twenty-one participants (13 CON, 8 PAT) had a less affected/dominant right arm, and seven participants (2 CON, 5 PAT) had a less affected/dominant left arm. Other participant characteristics are displayed in Table 2.

Missing data of participant's characteristics (age PAT, n = 1 and TIS PAT n = 1) resulted from missing data entry. Exhaustion (PAT on mobile seat, n = 1) and a misplaced electrode (Obliquus externus (OE) CON, n = 1) also led to missing data.

Ethical considerations

This research complied with the tenets of the Declaration of Helsinki. The study was juristically verified by the medical Ethics Committee of Canton Zurich (Req-2020-00569). All participants provided their written informed consent.

Apparatus

The movable seat is described in detail in separate publications and is therefore described only briefly here [24, 26]. The seat was designed for the rehabilitation of PAT to support the following therapy goals of the International Classification of Health Intervention (ICHI)—Interventions on Body Systems and Functions– 10 Interventions on the Musculoskeletal System– Movement (ICHI 1-10-MV) domain [27]:

Table 1. Inclusion criteria.

Healthy participants	People after stroke
Age $\geq$ 18 years	Age $\geq$ 18 years
BMI 18–28	BMI 18–28
No acute or chronic musculoskeletal, neurological or cardiopulmonary diseases	No acute or chronic musculoskeletal, neurological or cardiopulmonary diseases
No scoliosis	No scoliosis
No pregnancy	No pregnancy
Being able to understand verbal and written instructions in German	Being able to understand verbal and written instructions in German
	Being able to perform at least 2h of rehabilitation training a day
	TIS score between 2–19 points

BMI = body mass index, TIS = trunk impairment scale

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Table 2. Means and standard deviations of participant characteristics.

Characteristic [unit]	N	Mean	SD
BMI [kg*m^{-2}]	28	22.81	2.68
BMI people after stroke [kg*m^{-2}]	13	22.57	3.55
BMI healthy participants [kg*m^{-2}]	15	23.02	1.53
Age all participants [years]	27	47.85	22.56
Age people after stroke [years]	12	70.33	14.05
Age healthy participants [years]	15	29.87	5.34
TIS people after stroke [points]	12	12.67	3.84
Static sitting [points]	12	5.42	0.86
Dynamic sitting [points]	12	5.25	2.20
Coordination [points]	12	2.00	1.53

N = number of measurements, BMI = body mass index; TIS = trunk impairment scale; SD = standard deviation

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- MVD.PG.ZZ Assisting and leading exercise for control of voluntary movement functions

- MVF.PG.ZZ Assisting and leading exercise for involuntary movement

- MVD.PH.ZZ Training motor control.

The movable seat possesses either one or two degrees of freedom i.e. in medio-lateral and antero-posterior direction or a combination thereof. The seat is mounted on a U-shaped rail and, thus, rotates around a virtual axis located at the spine, allowing the upper torso to be maintained in an upright, calm position during lateral and flexural motion of the lower spine and pelvis. The ergonomic design has been previously explained in detail [28, 29]. All necessary safety requirements (e.g. pinching of body parts, securing the patient) were implemented according to current technical standards [30–32]. The seat can be locked in place to provide a stable seat or unlocked for mobile sitting. The latter allows the person to move the seat freely or keep it stable through active control.

Electromyography

Bilateral sEMG of M. multifidi (MF), M. erector spinae (ES), and M. obliquus externus were recorded using a myon sEMG system (myon AG Baar Switzerland; Type 142 RFTD-A01, D02-RFTD), at a sampling rate of 1200Hz and 12-bit resolution. To prepare the participants for sEMG measurements, the skin was first shaved and cleaned. Bipolar electrodes (Blue Sensor®, Ambu, Denmark, Type P-00- S, interelectrode distance: 20 148 mm) were then attached to the skin according to the recommendations of the sEMG of the Non-Invasive Assessment of Muscle Project (SENIAM) and Ng and colleagues [33, 34]. In both groups the same hardware was used, while the software for data collection was Vicon Nexus (Vicon, Oxford. UK, Version 2.11) in CON at the movement laboratory and proEMG (myon AG Baar Switzerland; Type 142 RFTD-A01, D02-RFTD) in PAT at the rehabilitation centre. Post processing was done with MATLAB software (MathWorks Inc., Natick, MA, USA, Version R2019A). The raw sEMG signals were high-pass, respectively low-pass filtered (Butterworth 2nd order, cut off frequency 30Hz respectively 500Hz). Subsequently, the root mean square (RMS), with a moving RMS window of 120 frames, was calculated and the maximal sEMG activity was then averaged from the five test repetitions in order to remove the power of potential intra-individual variability [35]. For PAT with possible muscle weakness, maximal voluntary contractions are not recommended to be performed [36, 37]. Therefore, maximal sEMG activity was calculated for each trial and

then standardized to the maximal muscle activity of static sitting on the stable seat (STAT). The percentage of maximal muscle activity relative to STAT (%STAT) was calculated as outcome variable. This was done to assess whether any given muscle was more or less active in comparison to static sitting, depending on the group, exercise, body side, or seat condition.

Trunk control exercises

During the one measurement session, participants received standardized oral instructions from one of the examiners and were able to practice the exercises prior to the tests. Each participant performed first STAT (Fig 1) and then two trunk control exercises, both on the stable and on the mobile seat with five repetitions. In the first exercise, participants were asked to initiate an isolated lateral flexion (LF) of their pelvis, and in the second to initiate an isolated LF of their trunk. If initial performance was poor, the instructions were repeated, and the participant received tactile feedback. During the "lateral trunk flexion" the participants sat upright on the seat, with their hip and knee angles flexed between 80° - 90°, their arms resting at their sides, and their feet placed on a footstool at hip width (Fig 2).

During the pelvis-initiated LF, participants were instructed to tilt the seat as far as possible to both sides while maintaining the upper body upright and as steady as possible. For the thorax-initiated LF, participants were instructed to reach as far as possible from the side of the chair to the floor, while keeping the seat surface as steady as possible and their full feet on the ground. In this way, the thorax was flexed, first to the right and then to the left, while the lumbar spine and pelvis were maintained as steady as possible. The order of the exercises was fixed for each participant, firstly on the stable and then on the mobile seat.

Statistical analysis

A 3-way within-subject linear mixed model was fitted to the data of each muscle separately with %STAT as the outcome of interest Y_i. In a first model all main effects were included, with β_0 representing the intercept, β_k the effect of the k-covariate and ε_i the independent and normal distributed errors $\varepsilon_i \sim N(0, \sigma^2)$. The covariates consisted of the between subject covariate: Group, the within-subject covariates: Side, Exercise, and Seat Condition, and the 2-way, 3-way, and 4-way fixed interaction effects.

$$\begin{aligned}
Y_i = \beta_0 &+ \beta_1 Group_i + \beta_2 Side_j + \beta_3 Seat_{Condition_j} + \beta_4 Exercise_j \\
&+ \beta_5 Group_i x Side_j + \beta_6 Group_i x Seat\_Condition_j \\
&+ \beta_7 Group_j x Exercise_j + \beta_8 Side_j x Seat\_Condition_j \\
&+ \beta_9 Side_j x Exercise_j + \beta_{10} Exercise_j x Seat\_Condition_j \\
&+ \beta_{11} Group_i x Side_j x Seat\_Condition_j \\
&+ \beta_{12} Group_i x Side_j x Exercise_j \\
&+ \beta_{13} Group_i x Exercise_j x Seat\_Condition_j \\
&+ \beta_{14} Exercise_j x Side_j x Seat\_Condition_j \\
&+ \beta_{15} Exercise_j x Side_j x Seat\_Condition_j x Group_i + \varepsilon_i
\end{aligned}$$

Each covariate had two levels, which were CON and PAT for group, less affected/dominant and affected/non-dominant for side, mobile and stable for seat condition, and pelvis- and thorax-initiated for exercise. The less affected side of PAT was equated to the dominant side of CON, whereas the affected side of PAT was equated to the non-dominant side of CON. A stepwise model selection procedure, with backwards optimization through exclusion of non-

Fig 1. Participant sitting in the static sitting position on the stable seat.

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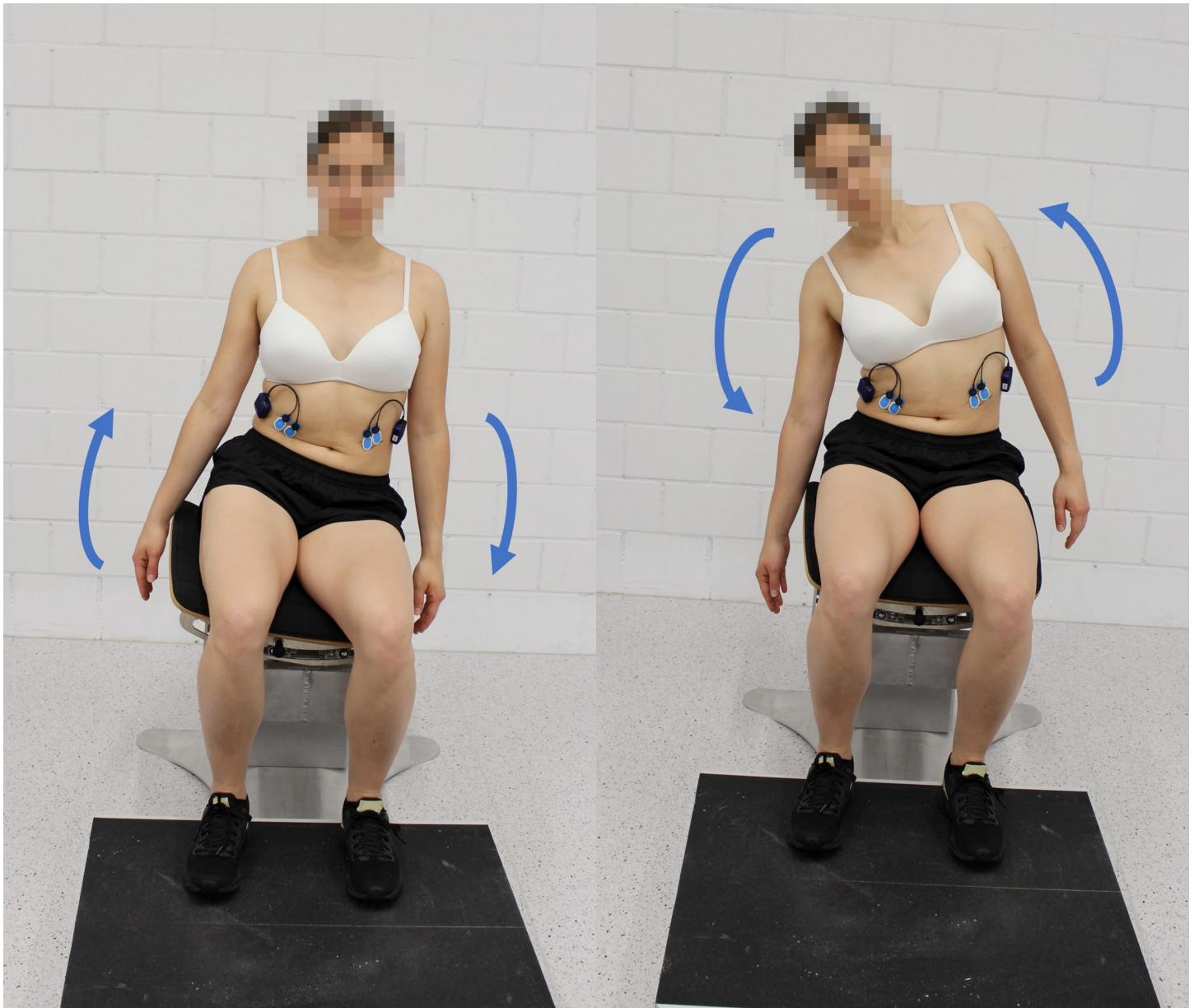
Fig 2. Trunk control exercises with movement initiated by the pelvis (left) and movement initiated by the trunk (right) on the mobile seat.

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significant covariates and the Akaike-Information-criterion was used to determine the final model. The aim of this procedure was to choose a parsimonious model to prevent overfitting of the data and ensure that the model is optimized for prediction, that is, for future data.

Descriptive statistics and statistical analysis were calculated with R Version 4.10 [38] and the packages lme4 [39], lmerTest [40], psych [41], emmeans [v1.6.2–1; 42], and ggplot2 [43]. Likelihood ratio tests revealed that 2-way, 3-way, and 4-way interactions could not be removed for MF, but for ES and OE the 4-way interaction could be removed. For ES, the factor side could be removed as well, resulting in a better model fit. In OE, a better model fit resulted when interactions with side were removed. The outcome variable was logarithmically transformed due to the distribution of the residuals. Significance level was set to $p < 0.05$.

Results

Descriptive data of each subgroup and each muscle can be found in the supplementary material. Additionally, predictive values and interaction plots are also available in the supplementary material. The results which are presented in this section all correspond to the predicted % STAT.

M. multifidi

There was a significant 4-way interaction effect for all factors (seat condition, group, side, and exercise), $F(1, 28.55) = 11.67$, p < .002. Additionally, a 3-way interaction effect for seat condition, group, and exercise was found, $F(1, 25.48) = 12.47$, p < .002.

As can be seen in Fig 3, the predicted %STAT in pelvis-initiated LF on the mobile seat was higher for CON and lower for PAT, compared to the stable seat. Thorax-initiated LF showed opposite results than pelvis-initiated LF, with lower %STAT on the mobile seat. The exception was the affected side of PAT where %STAT was higher on the mobile seat. Small differences between sides were present.

On the mobile seat peak muscle activity for CON during thorax-initiated LF was 2.5–3.1 times higher than in static sitting, respectively 2.1–2.4 times higher for PAT, whereas on the stable seat it was 3.4–4.1 times higher for CON and 1.8–2.1 times higher for PAT. CON showed 3.3–3.8 times higher peak muscle activity during pelvis-initiated LF than during static sitting on the mobile seat, while on the stable seat peak muscle activity was only 2.5 times
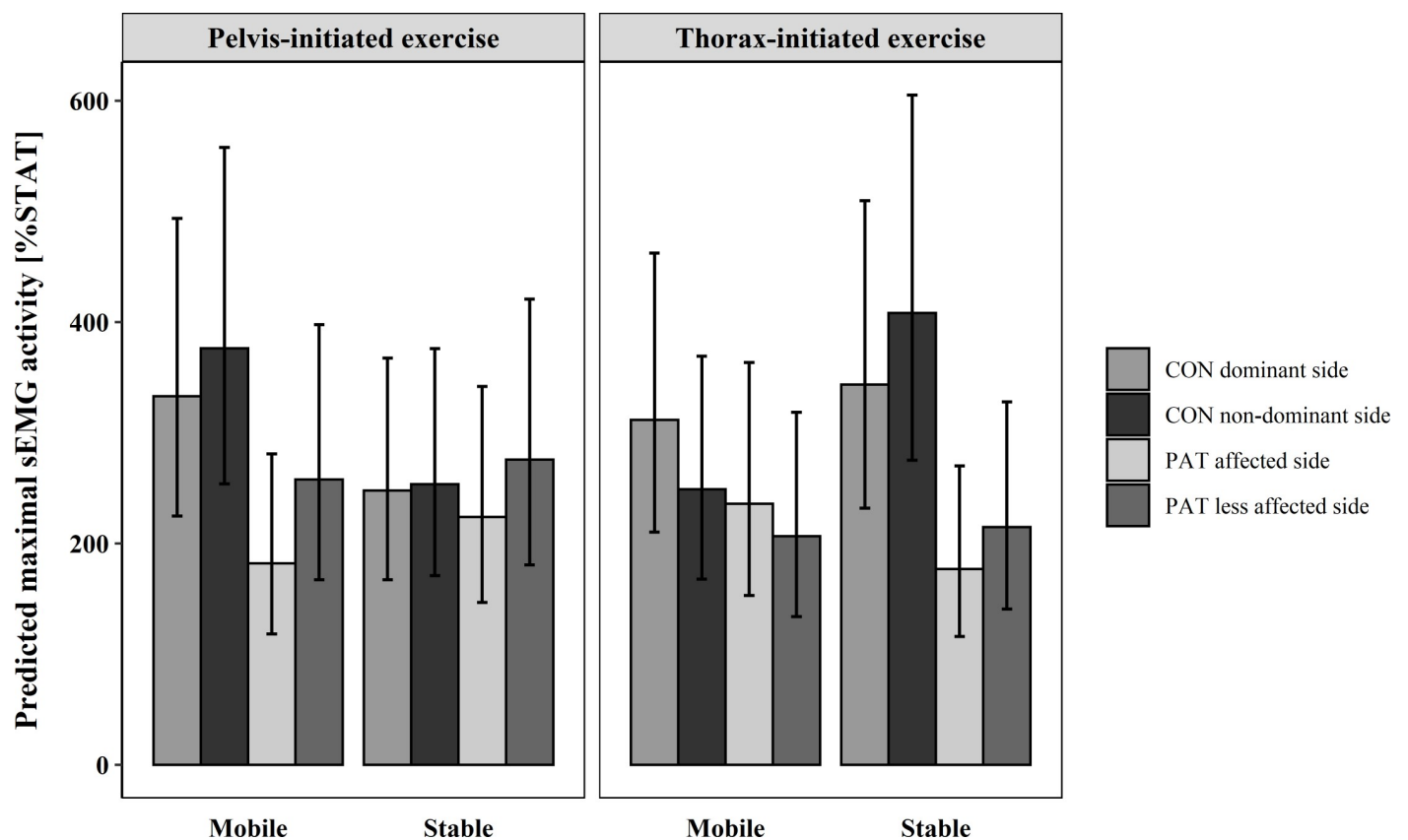
Fig 3. Predicted maximal sEMG activity and confidence level of each subgroup in M. multifidi. CON = healthy participants, PAT = people after stroke, % STAT = percentage of maximal muscle activity relative to static sitting on the stable seat.

higher. With 1.8–2.6 times higher activity on the mobile seat and 2.2–2.5 times higher activity on the stable seat, PAT showed lower variation than CON.
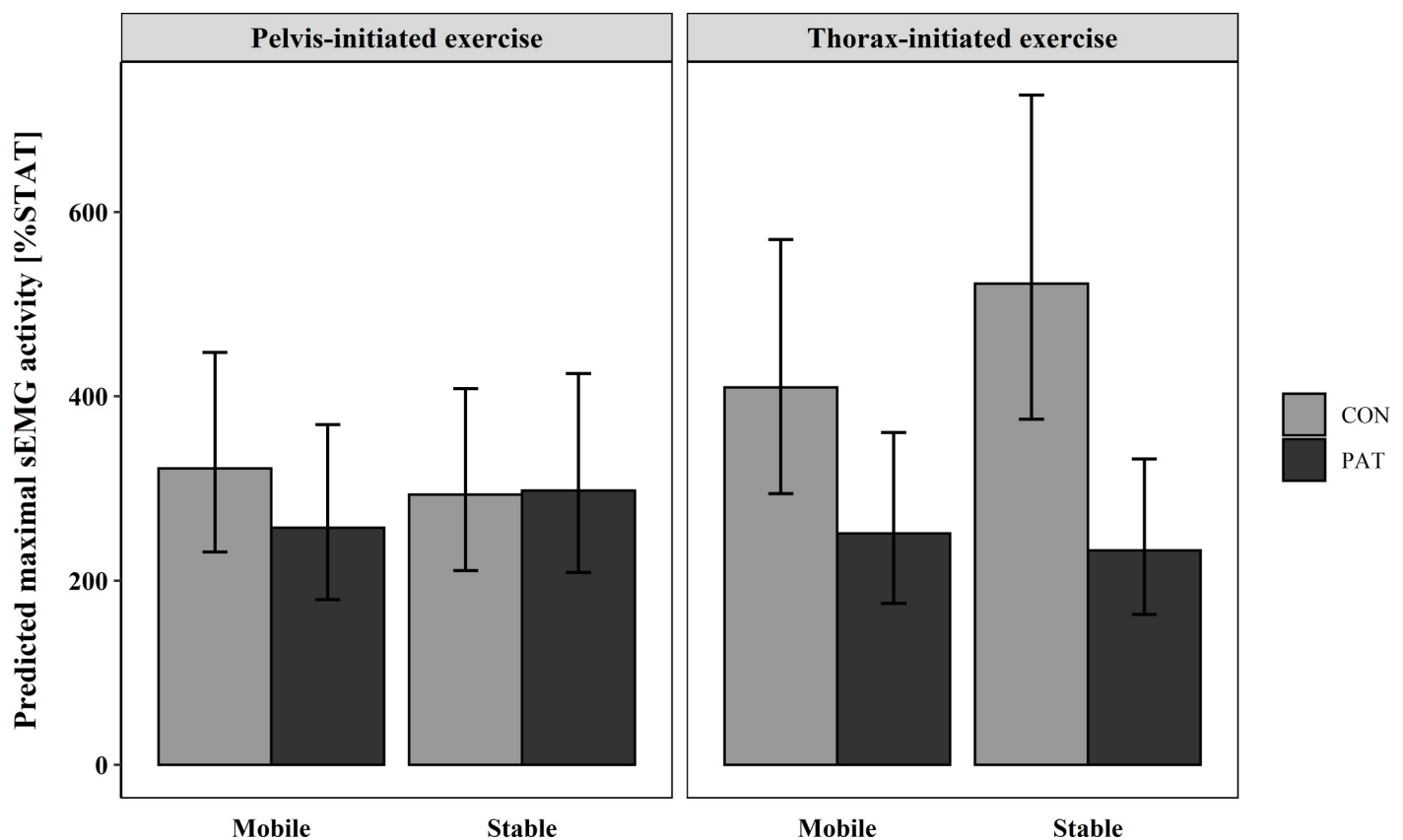
M. erector spinae

A statistically significant 3-way interaction effect for group, exercise, and seat condition was found for ES, $F(1, 25.66) = 6.95$, p = .014, as well as a 2-way interaction effect for exercise and group $F(1, 26.24) = 7.52$, p = .011.

Whereas the %STAT of ES on the mobile seat was higher for the pelvis-initiated LF in CON and for the thorax-initiated LF in PAT, higher %STAT on the stable seat was seen for the thorax-initiated LF in CON and for the pelvis-initiated LF in PAT (Fig 4). Additionally, CON had a higher %STAT than PAT, except for the pelvis-initiated exercise on the stable seat where the difference was very small. In general, the %STAT was higher for the thorax-initiated exercise in CON and for the pelvis-initiated exercise in PAT. Compared to static sitting, PAT had 2.3–3 times higher peak muscle activity, whereas CON had 2.9–5.2 times higher peak muscle activity, depending on the exercise and seat condition.

M. obliquus externus

OE showed a significant main effect for both group, $F(1, 25.67) = 33.81$, p < .001, and exercise $F(1, 24.59) = 38.65$, p < .001. Additionally, a significant interaction effect was found for the

Fig 4. Predicted maximal sEMG activity and confidence level of each subgroup in M. erector spinae. CON = healthy participants, PAT = people after stroke, % STAT = percentage of maximal muscle activity relative to static sitting on the stable seat.

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factors group and exercise, $F(1, 24.59) = 31.39$, p $<$ .001, and seat condition, group, and exercise, $F(1,24.11) = 6.62$, p = 0.017.

In both seat conditions and exercises, PAT showed a similar %STAT (Fig 5). In contrast, CON had a higher %STAT on the stable seat for the thorax-initiated LF, but not for the pelvis-initiated LF. A difference between groups for the thorax-initiated LF existed, with much higher %STAT of CON. Otherwise differences were much smaller. The %STAT of CON during the thorax-initiated LF was much higher than the %STAT of PAT. Side differences were very small on the stable seat, but on the mobile seat CON showed higher %STAT on the dominant side.

Whereas during the thorax-initiated LF of CON, peak muscle activity on the stable seat was 6.3–6.8 times the size of peak muscle activity during static sitting, respectively 8.3–8.9 times the size on the mobile seat, during the pelvis-initiated LF the peak muscle activity was only 2.3–2.8 times as high as the peak activity of static sitting. For PAT, peak muscle activity is 1.4–1.8 times higher on the mobile seat and 1.6–1.7 times higher on the stable seat.

Discussion

To the author's knowledge, this is the first study to investigate bilateral %STAT of trunk muscles comparing a stable and mobile seat during seated trunk control exercises, namely thorax- and pelvis-initiated LF, in both CON and PAT. Our research has shown that %STAT in PAT is higher on the mobile seat during the thorax-initiated LF and lower during the pelvis-initiated LF. In contrast, higher %STAT on the mobile seat was present in CON during the pelvis-initiated LF and

Fig 5. Predicted maximal sEMG activity and confidence level of each subgroup in M. obliquus externus. CON = healthy participants, PAT = people after stroke, %STAT = percentage of maximal muscle activity relative to static sitting on the stable seat.
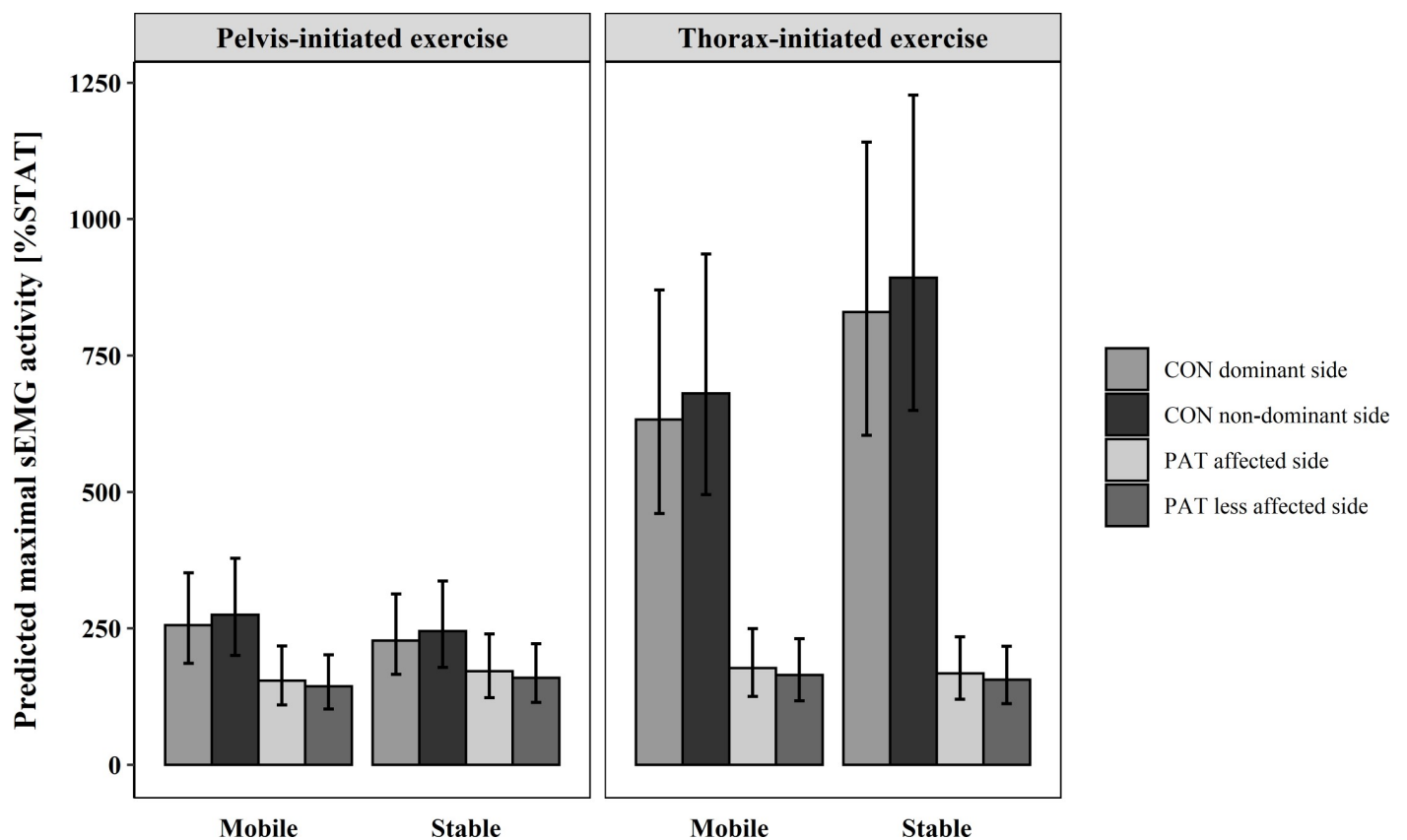
https://doi.org/10.1371/journal.pone.0272382.g005

lower during the thorax-initiated LF. But our results have also shown that during seated trunk control exercises, seat condition, exercise, and group affect the %STAT of trunk muscles. However, due to the 4-way interaction which was only present in MF, the investigated side does only interact with other factors in these muscles. 3-way interactions between different investigated factors were found in all three muscles. For this reason, it cannot be stated in which seat condition, side, group, or exercise %STAT is the highest, since it is dependent on the other factors.

Performing the exercise on the mobile seat, compared to the stable seat, led to higher %STAT during pelvis-initiated LF in CON, while for PAT this was the case when performing thorax-initiated LF. %STAT could either be higher on the mobile seat due to a possibly larger range of motion or due to more stabilization effort to keep the body in a stable position. Since there were differences depending on group and exercise, it is assumed that the larger range of motion only played a small role and primarily the stabilization effort of the muscles resulted in higher %STAT. It seems like CON use MF, ES, and OE to stabilize the upper part of the trunk on the mobile seat while moving their pelvis laterally, and PAT use these muscles to stabilize their hip and lower trunk when moving the thorax laterally. Existing literature suggests that the cross-sectional area of back muscles (MF) and the muscle activity of trunk muscles (upper and lower rectus abdominis) after training on a mobile surface like a Swiss Ball or plinth is increased compared to training on a stable surface [44, 45]. In a systematic review, Van Crie-kinge et al. (2019) reported that only the muscle activity of internal oblique muscles improved significantly after trunk training. Although not significantly, ES, OE, and rectus abdominis muscle activity still increased after trunk training, independent of the sitting surface. They concluded that, regarding the increase of muscle thickness and muscle activity, training on a mobile surface was more efficient than training on a stable surface [46]. Even though for each group only one exercise led to higher %STAT on the mobile seat, prior research suggests that training for a longer period on a mobile seat could be more efficient [44–46].

While during the pelvis-initiated LF, %STAT was around the same size in all muscles, during the thorax-initiated LF, %STAT differed between the muscles. In CON, with values between 632.86 and 892.63%STAT, the predicted %STAT was generally much higher in OE compared to MF and ES with values only between 248.92 and 522.33%STAT. Previous research has found that obliques act as prime movers during lateral bending [47], which could explain the higher %STAT of OE muscles compared to other muscles during thorax-initiated LF in CON. PAT showed similar %STAT in both exercises for MF and ES, only for OE %STAT was somewhat smaller than the two back muscles. This could either mean that PAT compensated with other muscles, that were not measured, or that they had a smaller range of movement either due to limited muscle strength or due to limited trunk control. Nonetheless, in all conditions and muscles the predicted %STAT was at least 1.4 times higher than peak muscle activity during static sitting, which suggests that the trunk musculature is engaged during lateral flexion exercises and could therefore result in a training effect.

Differences of %STAT between the affected and the less affected side exist for PAT, except for ES for which the covariate side could be removed. PAT have small coherence of antagonistic muscle pairs which could explain these findings [48]. Our findings that for ES the side difference was not significant, does not concur with the results of the study of Winzeler-Merçay and Mudie (2002). They compared muscle activity during sitting exercises in PAT and CON, which led to the conclusion that, for PAT, ES activation is higher on the affected side. [37]. In our study, the less affected side only showed higher %STAT in MF, which was not measured in their study. Cai et al. (2019) reported that the less affected side of OE and ES showed less average muscle activity than the affected side in PAT [49], which is partially in line with our results since ES did not show any side differences. Possible reasons for this difference are that the performed exercise in our study was LF initiated from the thorax and from the pelvis, while in the

study of Cai et al. (2019) side-to-side, up-and-down, and back-and-forth reaching exercises were performed and in the study of Winzeler-Merçay and Mudie (2002) sitting exercises were performed [37, 49]. Additionally, different outcomes of sEMG measurements were used.

In our CON group, significant side differences of %STAT were only present in MF and OE. While in OE %STAT was higher on the non-dominant side, in MF this was dependent on the exercise and seat. Both exercises were symmetrical which is why side differences in CON were surprising. Existing literature investigating trunk muscle activity or cross-sectional area of similar tasks showed side differences as well. Hides et al. (2008) found 5.2% asymmetry in the cross-sectional area of MF at the L2 vertebra of CON, while Farahpour et al. (2015) found a significant difference in agonistic and antagonistic muscle activity of ES in young and healthy controls during lateral bending while standing [50, 51]. Similar results were found by Kuriyama and Ito (2005) who stated that contralateral muscle activity, but not ipsilateral muscle activity, was present when bending laterally in healthy controls [52]. Both exercises were performed to the right and left side and are therefore symmetrical, which suggests that both sides were contralateral to the movement in one part of the exercise. Additionally, Pereira et al. (2011) found no difference in muscle activation onset between ipsi- and contralateral sides for symmetrical exercises [53] and therefore, the timing of both sides should be similar. However, Peach et al. (1998) state that peaking of muscle activity happens at different timepoints. While ipsilateral muscles peak at the change of direction, contralateral muscles peak during the rising movement [47]. In CON it can be assumed that muscle strength is similar in both sides and consequently %STAT of both sides occurred at the same point of the movement, either at the ipsilateral change of direction or the contralateral rising movement.

Exercise showed interactions with other factors in all three muscles. Therefore, a general statement regarding which exercise leads to lower %STAT, cannot be made. Contrast analysis for exercise differences showed that ES and OE behaved similarly, which is surprising due to the fact that ES is a lateral trunk extensor and OE is a trunk flexor and hence their function is different [53]. CON have higher %STAT during thorax-initiated LF while PAT have slightly higher %STAT during pelvis-initiated LF. For MF and OE (only of PAT), the seat condition plays an additional role. Thorax-initiated LF leads to higher %STAT on the stable seat in CON while in PAT higher %STAT is reached on the mobile seat. Higher %STAT of pelvis-initiated LF was seen in the corresponding conditions. The fact that, even though both exercises represent a trunk control exercise, the moving body parts are contrary to each other could explain the contrasting result. While during the thorax-initiated LF, the lumbar spine and pelvis were held as stable as possible, during the pelvis-initiated LF the thoracic and cervical spine were kept as stable as possible. When the sitting position is changed from slouched to upright through a lumbopelvic initiated pattern, the load (and possibly also the muscle activity) is smaller due to the proximity to neutral posture [54]. This fact could indicate that in CON, the range of motion during the pelvis-initiated LF is lower and that muscle activity is therefore lower as well. It is possible that the thorax-initiated LF on the mobile seat led to sensory inputs which were difficult to process for PAT and hence muscles were activated more even though it was possibly not necessary. Another possible explanation would be that pelvis-initiated LF was perceived as difficult by PAT due to sensory deficits after stroke and therefore, movement was kept to a minimum which resulted in lower %STAT.

The participant characteristics of the two groups investigated in this study were very different. It is likely that the observed group difference resulted due to the contribution of several factors as age, lifestyle, health condition or gender. Mean body mass index values of both groups were similar. CON were young, while PAT were older and, due to their condition, probably more sedentary. A sedentary lifestyle increases the risk of more subcutaneous fat which in turn, increases the risk of measurement error of sEMG [55]. But because mean body mass index

values were similar in both groups, this difference is expected to have a minimal impact. Furthermore, the mean score in the dynamic sitting subscale of the trunk impairment scale was only 5.25 from a maximum of 10 points. Since dynamic sitting exercises of the TIS are similar to our trunk control exercises, it can be assumed that PAT were limited in their trunk control and probably used compensation strategies which are shown through diverging muscle activity of the three investigated muscles. Also, trunk recovery is different depending on the side of hemiparesis [56]. Different stages of recovery in the PAT group could therefore explain a high variability of %STAT. With increasing age, muscles get activated earlier and there is more co-contraction. Additionally, the peak displacement for lateral bending is lower in older people [57]. Lower peak displacement suggests a lower muscle activity since the deviation from the stable, upright sitting axis is smaller. Thus, the muscular effort to return to this stable body axis is smaller which could explain differences between groups. Differences between males and females in sitting and standing posture have been reported [58], but the effect of an imbalance in the number of male and female participants is expected to be minimal since each participant's muscle activity was referenced to their own static sitting muscle activity.

Several limitations were present in the current study. Muscle activity was not normalized to each participants' individual maximal muscle strength, but to the %STAT without specific instructions on how much the muscles should be tensed, which might lead to a high variability of the data. Maximal voluntary contraction was not measured because of PAT's physical conditions and because physical contact was reduced to a minimum due to Covid-19. From literature, it is known that static sitting posture of PAT is less stable than static sitting posture of CON [59]. Therefore, higher variability of STAT could counteract variability of %STAT in PAT and in CON stable STAT and %STAT is assumed. Our sample size was small with only 15 CON and 13 PAT, which leads to a limited generalizability of results. The COVID-19 pandemic restricted the recruitment of participants, both in terms of the sample size and matching between the groups, for example in terms of age. Right-handed participants represented the majority and left-handed participants were underrepresented in the CON group. In PAT, the affected side was almost balanced between right and left. Furthermore, the dominant side of CON was equated with the less affected side of PAT and the non-dominant side of CON with the affected side of PAT, which might not be true in terms of muscle strength or muscle activity. In other studies, comparing sides of PAT and CON, the same approach was chosen [37]. Muscular activity is not always equivalent to muscle strength, especially in PAT, and it is therefore not known whether the mobile surface leads to greater trunk muscle strength. However, an almost linear relationship between sEMG amplitude and muscle force exists [60]. For this reason, it can be assumed that higher peak sEMG values lead to higher muscle force generation and that trunk muscles are more engaged when peak sEMG activity is high which in turn increases the possible training effect. Other limitations were usual limits of sEMG procedure, for example the influence of thermal conditions. The measurement protocol was designed in order to achieve measurement sessions which are as similar as possible.

In general, high standard deviations in our data suggest great variability between individuals and, therefore, the results must be interpreted cautiously. Further work with PAT and CON groups with a higher number of participants could clarify whether our results are generalizable. Similarly, studies with more than one measurement session could indicate whether there is a different training effect for each seat on trunk muscle activity as well as muscle strength.

Conclusion

Trunk control exercises on a mobile sitting surface could be an effective and safe training method for both PAT and for CON. Depending on the group and exercise, the mobile or the

stable sitting surface leads to higher %STAT. When a high muscular activity and therefore high muscle engagement is intended on the mobile surface, PAT are recommended to perform the thorax-initiated LF while CON are recommended to perform the pelvis-initiated LF. If, in contrast, a low muscle activity and therefore low muscle engagement on the mobile seat is intended, it is recommended that CON perform the thorax-initiated LF and PAT the pelvis-initiated LF. Further studies are needed to clarify which factors contribute to an effective training program including multiple sessions on the different sitting surfaces and whether training on one surface is more effective than on the other.

Supporting information

S1 File. Supplementary material–interaction plots.
(PDF)

S2 File. Supplementary material–predicted and descriptive sEMG data.
(DOCX)

S3 File. Minimal dataset.
(XLSX)

Acknowledgments

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