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Effects of motor practice on learning a dynamic balance task in healthy young adults: A wavelet-based time-frequency analysis

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ABSTRACT

Background: Previous research showed changes in amplitude- or time-derived measures of electromyographic (EMG) activity with motor learning. However, an analysis of the EMG spectral content (e.g., via wavelet technique) has not been included in these investigations yet.

Objective: The aim of this study was to use conventional, amplitude-derived EMG parameters along with modern, wavelet-based time-frequency EMG measures to assess the effects of motor practice on learning a dynamic balance task.

Methods: Nineteen young male adults (mean age: 26 ± 6 years) practiced a dynamic balance task for two days. Delayed retention test was performed on the third day. On a behavioral level, the root-mean-square error (RMSE) of the stability platform angle was calculated and used as outcome measure. On a neuromuscular level, EMG data from the tibialis anterior (TA) and the gastrocnemius medialis (GM) muscle were unilaterally recorded and analysed by calculating the integrated EMG (iEMG) and the EMG intensity (via continuous wavelet transforms).

Results: Two days of practice resulted in significantly improved balance performance (i.e., lower RMSE) and TA/GM activation (i.e., reduced iEMG and EMG intensity) that was still present during the retention test on day 3. There was also evidence of practice-related changes in the EMG intensity pattern as indicated by an intensity shift from higher to lower frequency components.

Conclusions: We conclude that motor practice leads to improvements in movement effectiveness as indicated by reduced RMSE and in movement efficiency (i.e., decreased iEMG and EMG intensity, intensity shift). In addition to conventional amplitude-derived EMG parameters, modern, wavelet-based time-frequency EMG measures are appropriate to detect practice-related changes in muscle activation.

1. Introduction

It is well known that motor practice leads to improvements in motor performance resulting in reductions in movement error and duration, or increases in the number of successful trials [1,2]. On a neuromuscular level, these performance enhancements are related to changes in various amplitude- or time-derived measures of electromyographic (EMG) activity [3]. In fact, Ludwig [4] examined alterations in performance and temporal EMG parameters associated with learning a target-oriented elbow extension task in young adults (age range: 18–22 years). Following practice, the participants increased their level of target accuracy and reduced their time to peak amplitude for the triceps brachii muscle. In another study, Hobart et al. [5] investigated the acquisition of a ball-throwing task in young adults (age range: 20–30 years). Practice resulted in a decreased throwing error and a reduced integrated EMG (iEMG) for the anterior deltoideus muscle.

There is further evidence concerning practice-related enhancements in postural control and muscular activity. For example, Van Dieën et al. [6] studied the effects of learning to balance on one leg in young adults (mean age: 23 ± 2 years). After 30 min of practice on a balance board, significant improvements in behavioral (i.e., reduced relative power of the board angle) and neuromuscular (i.e., decreased muscle activity) parameters were found. In addition, Silva and colleagues [7] assessed the impact of wobble board training on single-leg standing performance in young men. Four weeks of training resulted in significantly longer standing time and decreased lower-extremity muscle activation in the

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training compared to the control group. Results of the aforementioned studies [4–7] extended our knowledge about practice-related changes in motor performance, postural control and muscle activity in the time (e.g., time to peak muscle activation) and amplitude (e.g., iEMG) domain. However, studies analyzing changes in the time-frequency of the EMG signal (i.e., spectral content) accompanied with motor practice are still missing.

Analyses of the EMG spectral content may provide a more in-depth assessment of changes in muscle activation occurring with motor practice than conventional, amplitude- or time-derived measures of muscle activity. Although the Fourier transform represents the most common technique for assessing changes in the frequency domain, this method is inappropriate for the analysis of dynamic muscle actions where the EMG signal is non-stationary [8]. In addition, the Fourier transform does not allow a comprehensive examination of EMG data because frequency but no timing information from the signal is provided. To overcome these limitations, the present study uses wavelet transformation for the time-frequency analysis of EMG data. The wavelet technique represents a well-established method for the assessment of the spectral content of surface EMG during dynamic contractions [9]. For example, EMG signal analysis by wavelets were used for the examination of isokinetic knee extension movements under different loading conditions [10] and of running with different shoe conditions [11]. However, no study has applied wavelet analyses to investigate practice-related changes due to motor learning so far. Yet, motor learning should also be associated with changes at the time-frequency level (i.e., EMG intensity/power). Several studies [12,13] showed that motor practice improved mechanical and metabolic efficiency (i.e., indices of force/power, oxygen consumption, heart rate, and muscle activity). Regarding muscle activity as a measure of muscle metabolism, improved efficiency might lead not only to reduced EMG amplitude but also to a reduction in EMG intensity. Moreover, higher efficiency should also be illustrated in the frequency components of the EMG signal. That is, over the course of practice the intensity of higher frequency domains is likely to decrease and the intensity in lower frequency bands will increase. Evidence for this assumption is derived from studies [14–16] showing predominantly high-frequency components during fast anticipatory movements (e.g., during pre-activation or before heel-strike) that most frequently occur at the beginning of a learning process. Low-frequency components, on the other hand, predominantly occur during relatively slow and highly controllable movements (e.g., during loading-response or after heel-strike) that are typically necessary at the end of a learning process.

Thus, the present study aimed to investigate practice-related changes in the EMG spectral content by using continuous wavelet transformations paired with the analysis of conventional EMG amplitude and performance parameters while learning a dynamic balance task. On one hand, our study represents a replication of previous studies investigating muscle activation (i.e., iEMG) following motor practice. On the other hand, EMG intensity represents a new measure that illustrates changes in the time-frequency intensity pattern (spectral content) occurring with motor practice, that cannot be derived from conventional, amplitude- or time-derived measures. We expected that participants significantly enhance motor performance (i.e., less movement error) after practice. In terms of the myoelectric variables, we assumed a significant reduction in measures of EMG amplitude and intensity (i.e., less iEMG and EMG intensity). Further, we hypothesized an intensity shift, i.e., a decrease in high-frequency and an increase in low-frequency components.

2. Methods

2.1. Subjects

Nineteen healthy male college students (mean age: 26 ± 6 years) volunteered to participate in this study. Participants were recruited by posting flyers and by publishing a study call on the university website and had no prior experience with the experimental task. Students were excluded from study participation if they already had several weeks of balance practice experience because this could limit the training improvements of the experiment. None of them had any history of musculoskeletal, neurological or orthopedic disorder that could have affected their ability to execute the experimental procedure. All participants gave their written informed consent before the start of the study. The Human Ethics Committee at the University of Duisburg-Essen, Faculty of Educational Sciences approved the study protocol.

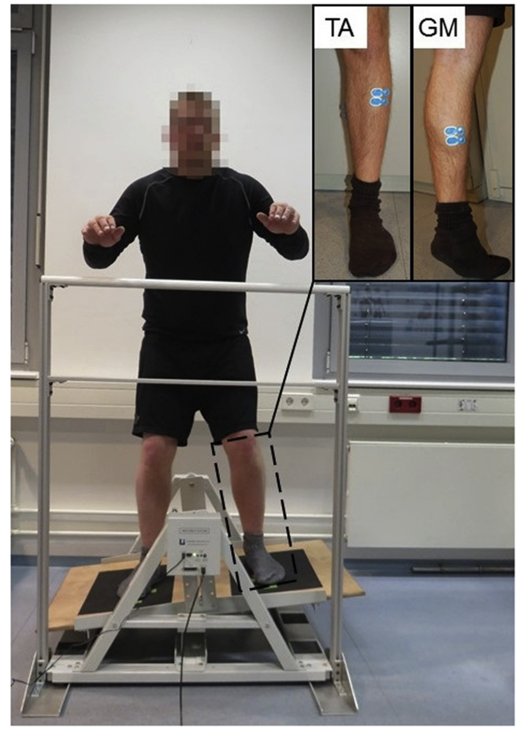

Fig. 1. Illustration of a participant balancing on the stability platform (stabilometer) while synchronously recording activity of the tibialis anterior (TA) and the gastrocnemius medialis (GM) muscle.

2.2. Experimental procedure

The motor task required participants to balance on a stability platform (Lafayette Instrument, Model 16030, Lafayette, LA, USA). The stability platform (stabilometer) consisted of a 65 × 107-cm wooden platform, allowing a maximum deviation of 15 degrees from the horizontal to either side of the platform (Fig. 1). A safety rail mounted to the stability platform was used to prevent participants from falling if they lost their balance. Participants were instructed to remain in balance, i.e., to keep the stability platform in a horizontal position (± 3 degrees) for as long as possible. Each trial started with the platform in horizontal position and arms grasping the safety rail. All participants performed seven 90-s practice trials on each of two consecutive days of acquisition. A 90-s rest interval was given between trials. Knowledge of results (i.e., time in balance) was provided after each trial. To assess learning of the dynamic balance task, the participants were tested (i.e., one 90-s trial) in a delayed retention test 24 h later (on day 3) without providing knowledge of results.

Circular (10-mm diameter), pre-gelled, self-adhesive, bipolar surface EMG electrodes (Ag/AgCl, BlueSensor N-00-S/25, Ambu Bad Nauheim, Germany) were used to unilaterally measure EMG activities of two muscles (m. tibialis anterior [TA], m. gastrocnemius medialis [GM]; Fig. 1) on the dominant leg (i.e., kicking leg). Both muscles encompass the ankle joint and play a dominant role in controlling posture during balancing on the stability platform. Electrodes were positioned longitudinally with respect to the underlying muscle fibre arrangement on the muscle bellies (center-to-center distance: 20 mm) in accordance to the European recommendations for surface electromyography (i.e., SENIAM) [17]. Inter-electrode resistance was kept below 5 kOhm (measured via EMG electrode impedance tester) by standard skin preparation that incuded shaving, slightly roughening, degreasing, and disinfecting the skin. EMG signals were amplified by a factor of 2000 and recorded telemetrically (transmission frequency: 2.4 GHz) using Myon 320 software (myon AG, Schwarzenberg, Switzerland) to a stationary computer using a sampling frequency of 2000 Hz per channel. EMG activity of both TA and GM muscle was simultaneoulsy recorded during the first trial of acquisition on day 1 and day 2 as well as on the delayed retention test on day 3. The position of the EMG electrodes was marked with indelible ink to ensure consistent placement over days. In order to reduce movement artifacts, electrodes were fixed with fish-net stockings and cables with adhesive tape. Platform position data and the associated EMG signals were synchronously recorded.

2.3. Data analyses

With respect to the behavioral data, a timer measured time in balance at a sampling rate of 25 Hz. Time in balance was computed when the platform was within ± 3 degrees of the horizontal position. Additionally, platform position data were exported from the analysis software PsymLab (Lafayette, LA, USA) for further analyses and used to calculate the root-mean-square error (RMSE) of the stability platform angle in degrees.

In terms of conventional, amplitude-derived EMG parameters, the analysis of the EMG data was performed using Matlab software version R2017a (The MathWorks Inc., Natick, MA, USA). In accordance to the SENIAM guidelines, EMG signals were filtered (low-pass: 500 Hz, high-pass: 20 Hz; second-order Butterworth filter) and full-wave rectified [18]. Additionally, mean baseline activation was subtracted with the electrodes attached to the participant while standing still in front of the platform. To create the linear envelope of the EMG signal, the root-mean-square was calculated using a gliding-window technique with a time window of 50 ms. Afterwards, the EMG signal was normalized to values obtained from a maximum voluntary isometric contraction (MVIC). MVIC was assessed on each day in a neutral position of the foot by using a custom-made machine [19]. Finally, the iEMG was calculated across the entire 90-s trial duration.

With respect to modern, wavelet-based spectral EMG measures, the analysis of the EMG data was executed using proEMG software (Prophysics AG, Kloten, Switzerland). Raw EMG signals were decomposed into time and frequency parts of the EMG intensity using the wavelet transformation algorithms described by Barandun et al. [20] and von Tscharner [21]. The wavelet transformation yielded the intensity (square root of power) of the EMG that was resolved in 21 Cauchy wavelets with the following rounded center frequencies: 2, 7, 13, 22, 33, 46, 61, 78, 97, 118, 141, 166, 194, 223, 254, 287, 322, 360, 399, 440, and 483 Hz. The selection of these frequencies is justified by studies [10,22] showing a fine resolution of the frequency bands between 20 and 100 Hz (Piper-Rhythm). Additionally, the range of 120–190 Hz is suggested in order to detect changes in the frequency space of a dynamic movement [23,24]. For example, von Tscharner et al. [23] combined wavelet and principal component analysis of EMG intensity patterns during running and isolated four relatively distinct frequency bands with one of them located in the aforementioned range. Further, these frequencies were selected to allow a better comparability with those used by fast Fourier transformations. Lastly, the presence of potential movement artifacts, particular in low wavelet frequencies, are plainly visible and recognizable, allowing a safe removal of these artifacts without any effect on the raw data set. For each wavelet, the EMG intensity was then calculated across the entire 90-s trial periods (i.e., intensity pattern). Subsequently, the intensities were summed across all 21 frequency bands to determine total EMG intensity. For the detection of a potential frequency shift in EMG intensity that might have occurred during practice, we subdivided the frequency spectrum into equal frequency ranges representing low- (i.e., 2–223 Hz, corresponding to wavelet 1–14) and high-frequency components (i.e., 223–483 Hz, corresponding to wavelet 14–21), at which a certain overlap can occur [24]. This procedure is in accordance to the work of von Tscharner and Goepfert [14].

2.4. Statistical analyses

An a priori power analysis using G * Power 3.1.9.2 [25] with the following input parameters was conducted to obtain a large-sized effect of ‘Day’: type I error ($\alpha = 0.05$), type II error ($1\text{-}\beta = 0.95$), number of groups ($n = 1$), number of measurements ($n = 3$), and correlation among repeated measures ($r = 0.50$). Our power analysis revealed a total sample size of $N = 18$ participants. Behavioural and neuromuscular data are reported as means and standard deviations after normal distribution was confirmed by the Shapiro-Wilk test, $p > 0.05$. For the detection of practice effects, RMSE values were analysed in a 2 (day: day 1, day 2) × 7 (trial: trial 1–7) analysis of variance (ANOVA) with repeated measures on days and trials. To detect learning effects, a paired sample *t*-test was used to quantify differences between the first trial on day 1 and the delayed retention test on day 3. With respect to EMG data, an ANOVA with repeated measures was used to calculate differences for the iEMG and total EMG intensity between acquisition (first trial on day 1 and day 2) and delayed retention test (day 3). In case of statistically significant differences, Bonferroni corrected post hoc Student’s *t*-tests were conducted. Further, Cohen's *d* was calculated to determine whether a statistical difference was practically meaningful as small ($0 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$) or large ($d \geq 0.80$). All analyses were performed using the Statistical Package for Social Sciences version 24.0 and significance level was set at $p < 0.05$.

3. Results

3.1. Behavioral level: Root-mean-square error (RMSE) of the stability platform angle

As can be seen from Fig. 2, participants decreased their RMSE across the two days of practice. The Day × Trial ANOVA revealed statistically significant main effects of day ($F_{(1, 18)} = 173.371$, $p < 0.001$, $d = 6.21$) and trial ($F_{(6, 108)} = 77.814$, $p < 0.001$, $d = 4.16$). Additionally, we found a significant Day × Trial interaction ($F_{(6, 108)} = 18.939$, $p < 0.001$, $d = 2.05$), indicating relatively greater improvements on day 1 than on day 2. In addition, the paired sample *t*-test showed significantly lower values in the delayed retention test on day 3 compared to the first trial of day 1 ($t = 14.067$, $p < 0.001$, $d = 2.56$).

3.2. Neuromuscular level: integrated EMG

Fig. 3 illustrates that participants decreased both iEMG of the TA and the GM muscle from day 1 over day 2 to day 3. ANOVA with repeated measures yielded a statistically significant main effect of day for the TA ($F_{(1, 18)} = 13.136$, $p < 0.001$, $d = 1.71$) and the GM muscle ($F_{(1, 18)} = 11.074$, $p < 0.001$, $d = 1.57$). Post-hoc comparisons revealed that the iEMG value of the TA ($d = 1.70$–2.57) and GM muscle ($d = 1.57$–2.07) was significantly higher on day 1 as on day 2 and day 3.

3.3. Neuromuscular level: EMG intensity

Fig. 4 shows a decrease in total EMG intensity from day 1 over day 2 to day 3 for the TA and the GM muscle. ANOVA with repeated measures revealed a statistically significant main effect of day for the TA ($F_{(1,}$

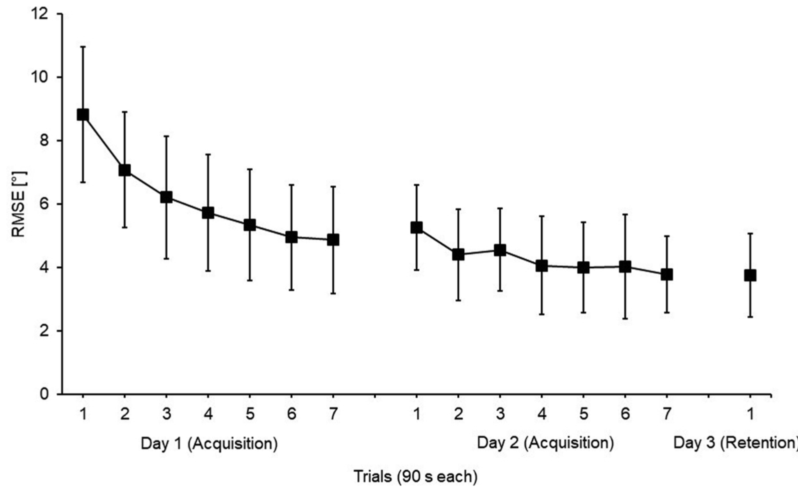

Fig. 2. RMSE during acquisition (day 1 and day 2) and delayed retention test (day 3). Values represent means and standard deviations. RMSE = root mean square error.

$_{18)} = 13.632$, $p < 0.001$, $d = 1.74$) and the GM muscle ($F_{(1, 18)} = 11.932$, $p < 0.001$, $d = 1.63$). Post-hoc comparisons yielded that total EMG intensity of the TA ($d = 1.97$–2.18) and GM muscle ($d = 1.56$–2.11) was significantly larger on day 1 compared to those on day 2 and day 3.

Fig. 5 displays the EMG intensity for each frequency band (wavelet) of the TA and the GM muscle comparing acquisition (day 1) with delayed retention test (day 3). The intensity pattern of the TA muscle changed from day 1 to day 3 as indicated by an increased intensity (1–11%) in low-frequency components (Fig. 5A; i.e., 2–97 Hz region that corresponds to wavelet 1–9) and a decreased intensity (2–8%) in high-frequency components (Fig. 5A; i.e., 118–322 Hz region that corresponds to wavelet 10–17). For the GM muscle, we observed an increased intensity (1–16%) in low-frequency components (Fig. 5B; i.e., 2–22 Hz region that corresponds to wavelet 1–4) and a decreased intensity (1–4%) in high-frequency components (Fig. 5B; i.e., 141–223 Hz region that corresponds to wavelet 1 1-14) from day 1 to day 3.

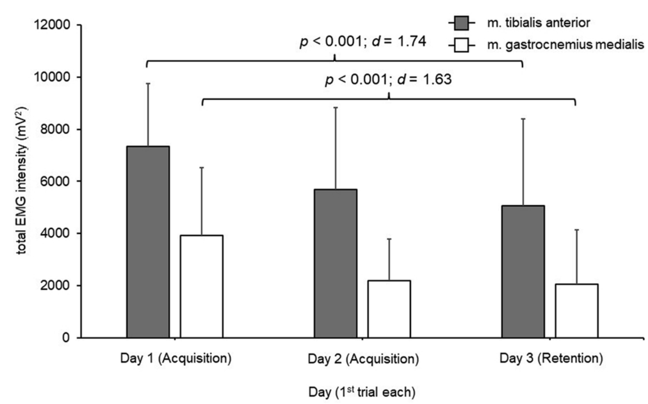

Fig. 4. Total EMG intensity of the tibialis anterior and the gastrocnemius medialis muscle during acquisition (day 1 and day 2) and delayed retention test (day 3). Values represent means and standard deviations. The horizontal lines including *p*- and *d*-value belong to the statistical results of the ANOVA with repeated measures to investigate the main effect of 'Day'.

4. Discussion

In the present study, we studied the effects of motor practice on learning a dynamic balance task in healthy young adults using conventional, amplitude-derived EMG parameters on one hand, along with modern, wavelet-based estimates of muscle activation that have not been investigated so far. In accordance with our hypothesis, we found that participants significantly improved their balance performance (i.e., decreased RMSE) over the course of practice. Further and in line with

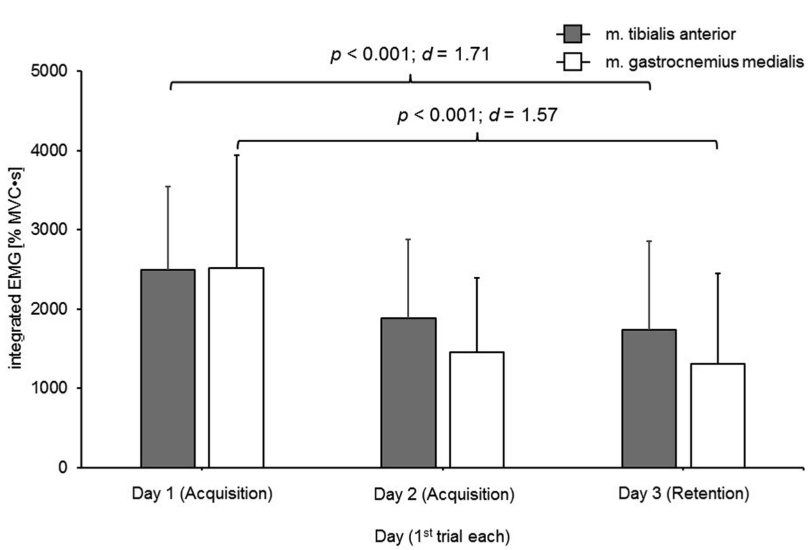

Fig. 3. Integrated EMG of the tibialis anterior and the gastrocnemius medialis muscle during acquisition (day 1 and day 2) and delayed retention test (day 3). Values represent means and standard deviations. The horizontal lines including *p*- and *d*-value belong to the statistical results of the ANOVA with repeated measures to investigate the main effect of 'Day'.

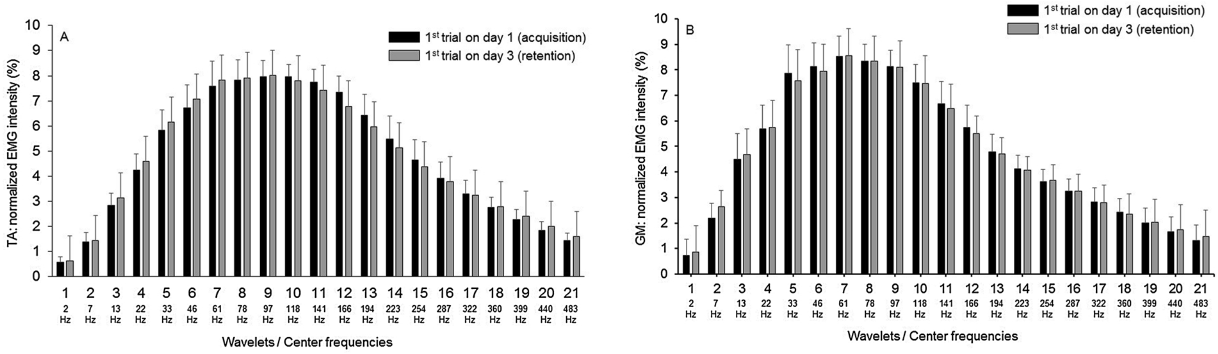

Fig. 5. Normalized EMG intensity (%) for each wavelet / center frequency (in Hz) of the tibialis anterior muscle (A) and the gastrocnemius medialis muscle (B) comparing acquisition (day 1) with delayed retention test (day 3). Values represent means and standard deviations. TA = tibialis anterior muscle; GM = gastrocnemius medialis muscle.

our assumptions, we detected significant decreases in measures of EMG amplitude and intensity of the TA and the GM muscle following practice.

Across two days of motor practice, our participants significantly reduced their movement error. In addition, the performance level observed at the end of practice was maintained in the delayed retention test. This is in line with our prediction and with previous studies that also used the stabilometer device for practicing the dynamic balance task [26,27]. Therefore, we conclude that motor practice lead to a refined level of postural control.

Over the course of practice, the iEMG values for the TA and the GM muscle significantly decreased and were still reduced in the delayed retention test. This finding is in accordance with our assumption, and fits well with the results from earlier studies that investigated practice-related changes on measures of EMG amplitude. For example, Moore and Marteniuk [2] investigated the acquisition of a time-constrained horizontal forearm extension in college-aged adults. As a result of practice, the participants reduced their movement time and their average EMG amplitude for the triceps brachii muscle. Further, Aggelousis et al. [28] examined young adults (age range: 19–26 years) who practiced a target-oriented ball throw. The authors observed a reduction in distance from target and in EMG amplitude for the biceps brachii and the brachioradialis muscle. Lastly, Lay et al. [12] studied young adults (age range: 18–21 years) that rowed an ergometer for ten practice sessions. Over practice, movement coordination improved and iEMG values from the biceps brachii and the vastus lateralis muscle decreased. Our finding of enhanced muscle activity following practice is not only in line with the aforementioned studies using motor control tasks [2,12,28] but also corresponds to studies that analyzed postural control tasks [7,29–31]. In this regard, Gruber et al. [30] investigated the effects of four weeks of balance training on measures of dynamic postural control and muscle activity in young adults. The authors reported significant reductions in postural sway and EMG amplitude during a 40-s one-legged stance test for the training compared to the control group. Furthermore, the effects of conventional versus reactive balance training in young adults (mean age: 24 ± 3 years) were investigated by Krause et al. [29]. Following four weeks of training, both modalities resulted in improved postural control and shank muscle activation during tests of stance and gait perturbation. Finally, Taubert and coworkers [31] examined practice-related changes following acquisition (i.e., once a week over six consecutive weeks) of the stabilometer task that was used in the present study. They found a significantly increased time in balance as well as a reduced coactivation between the left and right limb for the soleus muscle. There are various explanations for an enhanced muscle activation due to motor practice. In the present study and in earlier experiments [1,2], it has been shown that practice resulted in skilled motor performance (e.g., reduced error or increased number of successful trials) that is indicative of an enhanced movement effectiveness. In turn, improvements in movement effectiveness are related to changes in movement efficiency that include analysis of oxygen consumption, heart rate, and muscle activity [13]. For the latter, a practiced task is considered skilled or efficient if the task is completed with a minimum of energy expenditure that is reflected by a reduced level of muscular activation (e.g., lower iEMG) [12]. Thus, our results suggests that motor practice did not only lead to refinements in postural control while balancing on the stabilometer, but also to a more efficient activation of the TA and the GM muscle.

As expected, the EMG intensity for the TA and the GM muscle significantly decreased from the first to the second day of practice, and was again reduced in the delayed retention test on day 3. Previous studies showed that EMG intensity is sensitive to intervention-based changes in motor control. For instance, Napoli et al. [32] assessed the effects of strength training in young adults (mean age: 23 ± 3 years). Using pneumatic machines during training resulted in significantly higher EMG intensities as compared to weight-stack machines when movement speeds were similar in both groups. They concluded that pneumatic instead of weight-stack machines should be used if the goal of strength training is to increase muscular power. In another study, Huber and colleagues [10] compared sprint- versus endurance-trained athletes while performing isokinetic knee extensions. Wavelet analyses showed significant differences in the EMG spectra (i.e., higher intensities in the lower frequency components for the sprinters compared to the runners) that were specific for the various training regimes (i.e., speed versus endurance training). However, it still remained open if and how EMG intensity is affected by motor practice. The present observation of significant reductions in EMG intensity for the TA and the GM muscle represents a new finding on the effects of motor practice that corresponds to well-established parameters, such as iEMG. Thus, the argument of improvements in movement efficacy [12,13] seems also suitable to explain the reduction in total EMG intensity. Although, muscle activity was reduced after practice, participants improved performance in postural control which is indicative of an improved movement efficiency. Additionally, in both muscles we found that the intensity in higher frequency components decreased and that the intensity in lower frequency components increased from day 1 (acquisition phase) to day 3 (retention test). This finding is also indicative of an economization of muscular activation. In order to stabilize posture, slow-twitch fibers seem to be stronger innervated compared to the fast-twitch fibers of the same muscle (i.e., intensity shift from higher to lower frequency domains in the wavelet analysis). According to Weytjens and van Steenberghe [33], the intensity shift in the EMG spectra further suggests an improved synchronization of motor units, indicating enhanced movement coordination and motor performance [34,35]. However, further research is needed to clarify this interpretation.

5. Conclusions

To the best of our knowledge, this is the first study that used wavelet-based time-frequency analyses not utilized before, along with conventional, amplitude-derived EMG computations to assess practice-related changes, while learning a dynamic balance task in healthy young adults. It was shown that balance performance improved during two days of practicing the stabilometer task, as indicated by significant reductions in the RMSE values, and was still reduced in the delayed retention test on day 3. Further, EMG amplitude and intensity analysed for the TA and the GM muscle significantly decreased across practice trials and was still diminished during retention testing. A practice-related reduction in EMG amplitude represents a replication of previous study results [2,12,28] and has been explained by improved movement efficacy. In other words, motor learning leads to improved motor performance although muscle activation is decreased. Results from EMG intensity in our study represent a new insight and extent the current literature. More specifically, being able to show practice-related reductions in EMG intensity and an intensity shift from higher to lower frequency bands provide additional insights in adaptation mechanism when the goal is to prevent or treat musculoskeletal disorders. These findings suggest practice-related improvements in movement effectiveness (i.e., movement error) and efficiency (i.e., muscle activation). The present findings may contribute to further enhance our understanding of the underlying mechanisms of motor practice and learning in relation to performance improvements of balance movement.

Conflict of interest statement

None of the authors has any conflicts of interest.

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