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Responses in knee joint muscle activation patterns to different perturbations during gait in healthy subjects

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ABSTRACT

Purpose: To compare the responses in knee joint muscle activation patterns to different perturbations during gait in healthy subjects.
Scope: Nine healthy participants were subjected to perturbed walking on a split-belt treadmill. Four perturbation types were applied, each at five intensities. The activations of seven muscles surrounding the knee were measured using surface EMG. The responses in muscle activation were expressed by calculating mean, peak, co-contraction (CCI) and perturbation responses (PR) values. PR captures the responses relative to unperturbed gait. Statistical parametric mapping analysis was used to compare the muscle activation patterns between conditions.
Results: Perturbations evoked only small responses in muscle activation, though higher perturbation intensities yielded a higher mean activation in five muscles, as well as higher PR. Different types of perturbation led to different responses in the rectus femoris, medial gastrocnemius and lateral gastrocnemius. The participants had lower CCI just before perturbation compared to the same phase of unperturbed gait.
Conclusions: Healthy participants respond to different perturbations during gait with small adaptations in their knee joint muscle activation patterns. This study provides insights in how the muscles are activated to stabilize the knee when challenged. Furthermore it could guide future studies in determining aberrant muscle activation in patients with knee disorders.

1. Introduction

Muscle activation plays an important role in stabilizing the knee and drives knee function during dynamic activities of daily life such as gait (Sangwan et al., 2014). Alterations in muscle activation are frequently observed in patients with knee osteoarthritis (OA) (Mills et al., 2013) or with previous knee injuries (anterior cruciate ligament injury (Ingersoll et al., 2008) or meniscal tear (Sturnieks et al., 2011)). These alterations in muscle activation, like for example increased co-contraction during gait, will cause abnormal loading of the joint which could eventually lead to cartilage degeneration (Hodges et al., 2016; Trepczynski et al., 2018). Investigation of muscle activation is therefore needed in order to better understand these mechanisms and to develop treatments to improve muscle activation. However, a lot is still unknown on how healthy subjects control muscle activation of their knee muscles during daily activities such as gait, especially when the function of the knee is challenged. Such reference is essential when alterations in muscle activation of the pathological knee are studied.

Gait analysis with controlled perturbations can be used to mimic the situations during life that require muscle activation to stabilize the knee joint and maintain knee function (Chmielewski et al., 2005; Kumar et al., 2014; van den Noort et al., 2017). Previous studies have investigated muscle activation during perturbed gait in patients with knee osteoarthritis (Baker et al., 2019; Kumar et al., 2014; Schmitt and

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Rudolph, 2008) or ACL injury (Chmielewski et al., 2005; da Fonseca et al., 2004; Lustosa et al., 2011). However, most of these studies investigating muscle activation in response to perturbations during gait were limited to one type and intensity of perturbation, retaining the questions how subjects will respond to different types of perturbations (e.g. slip and sway perturbations) and what perturbation intensity to use to evoke the largest response. Testing subjects with different types of perturbations at the right intensity provides insight in how muscle activation is altered in response to different challenges experienced in daily life. A few studies have investigated several types of perturbations in healthy participants (Roeles et al., 2018) or stroke patients (Punt et al., 2017), however without measuring muscle activation around the knee. Previous studies from our department explored the effect of different perturbations (intensity and type) on the knee angles (van den Noort et al., 2017) and calf muscles of healthy participants (Sloot et al., 2015), but the knee joint muscle activation patterns of these previously collected datasets were not investigated. Therefore, the aim of this study was to compare the responses in knee joint muscle activation patterns to different types and intensities of perturbations during gait in healthy subjects.

2. Methods

2.1. Participants

This study used gait datasets of the participants measured in the studies by van den Noort et al. 2017 (van den Noort et al., 2017) and Sloot et al. (Sloot et al., 2015). Nine young healthy participants (four female) were included in this study, with an age of 24.4 ± 1.7 years and body mass index of 23.1 ± 2.1 kg/m^2. Exclusion criteria were a former surgery or current injuries to the lower extremities. All participants provided written informed consent. The study was approved by the ethics committee of the faculty of human movement sciences of the VU University Amsterdam.

2.2. Measurement protocol

The participants were measured in the gait laboratory of the department of rehabilitation medicine, Amsterdam UMC, location VUmc. The gait laboratory consists of a split-belt instrumented treadmill with a virtual reality environment (Fig. 1, GRAIL system, Motekforce Link BV, Amsterdam, the Netherlands). Furthermore, it has ten infrared motion capture cameras (VICON, Oxford, United Kingdom), two force plates imbedded in the treadmill and surface electromyography (EMG) (Cometa, Milan, Italy).

The session started by preparing the participants for walking on the treadmill by placing 24 mm EMG gel electrodes (Kendall H124SG, Covidien, Germany, inter-electrode distance 24 mm, discs, Ag/AgCl), according to the SENIAM guidelines (Hermens et al., 2000), on the vastus medialis (VM), rectus femoris (RF), vastus lateralis (VL), semitendinosus (ST), biceps femoris (BF), medial gastrocnemius (MG) and lateral gastrocnemius (LG) of the right leg. Furthermore, reflective markers were placed following the calibrated anatomical systems technique (CAST) marker model of Cappozzo et al. 1995 (Cappozzo et al., 1995). The participants walked with comfortable walking shoes at a fixed walking speed of 1.2 m/s and with a safety harness to prevent falling. The virtual reality screen was on during the measurement with the sole purpose of having a virtual environment to walk through. No visual perturbations were added. Walking on the treadmill started with a familiarization trial of five minutes, in which the participants could try the lowest and highest perturbation intensity of each type of perturbation. After this, an unperturbed walking trial of three minutes was recorded. In the following 20 walking trials, of each three minutes, perturbations were applied on the right leg according to the perturbation protocol.

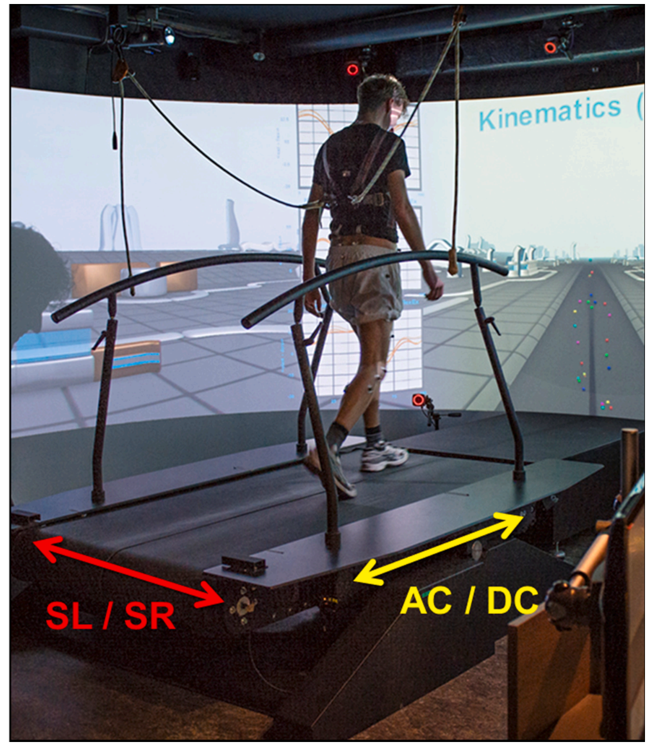

Fig. 1. The experimental setup with the instrumented treadmill that can apply four perturbation types. AC. acceleration of one belt, DC. deceleration of one belt, SL. sway left and SR. sway right.

2.3. Perturbation protocol

Four types of perturbations were applied on the right leg (Fig. 1), two sideway perturbations which were a sway left (SL) or sway right (SR) and an acceleration (ACC) or deceleration (DEC) of one of the two belts of the split-belt treadmill. Each type of perturbation was applied at five different intensities. The intensities (I1-I5) for the sway perturbations were 2–5 cm translation (increments of 0.75 cm) with a peak velocity between 0.1 and 0.2 m/s (van den Noort et al., 2017) and for the ACC and DEC perturbations a change in walking speed of 0.1–0.5 m/s (increments of 0.1 m/s) of the right belt of the treadmill with regard to the other (Sloot et al., 2015). Full details on the perturbations (e.g. duration and timing) can be found in previous publications (Sloot et al., 2015; van den Noort et al., 2017). The start of the perturbation was timed at heel strike, estimated using heel and sacrum marker data. This resulted in a perturbation during the stance phase of the right leg (~15–50% of the gait cycle). The time interval between perturbations was randomized between 10 and 15 strides. In each perturbed walking trial one type of perturbation was tested with varying intensity (random order) until 15 perturbed strides were collected. In total 20 perturbed walking trails, were collected.

2.4. Data analysis

The recorded EMG signals (sampled at 1000 Hz) were high-pass filtered (20 Hz, 3rd order, Butterworth), rectified and two-way low-pass filtered (6 Hz, 2th order, Butterworth) using Matlab (Matlab 2015, The Mathworks, Massachusetts, USA) to obtain the EMG envelopes. The EMG envelopes were divided into strides using initial contacts and toe-offs determined with the force plate data and a cubic interpolation function was used to normalize the strides to percentage of gait cycle. Furthermore, the muscle activation patterns of unperturbed gait were amplitude-normalized for each gait cycle to the peak activation that occurred during that gait cycle (Halaki and Ginn, 2012). The muscle activation patterns of perturbed gait were amplitude-normalized to the average peak activation of each gait cycle observed during unperturbed gait. The strides during the unperturbed walking trial were ensemble-averaged over at least 120 strides per participant. The strides during the perturbed walking trials were ensemble-averaged over 15 strides per perturbation type, intensity and participant. Mean values over full gait cycle, peak values and co-contraction indices were calculated of the ensemble-averaged muscle activations patterns of each participant. The co-contraction indices (CCI) of the lateral muscles (VM vs. ST), medial muscles (VL vs. BF) and quadriceps vs. hamstrings (VM, RF, VL vs. ST, BF) were calculated according to the following equation (1) (Matlab 2015, The Mathworks, Massachusetts, USA):

$$CCI(i) = 1 - \frac{|EMG_{ag}(i) - EMG_{ant}(i)|}{EMG_{ag}(i) + EMG_{ant}(i)} \tag{1}$$

In this equation the $EMG_{ag}(i)$ represents the muscle activity of the agonist muscle and $EMG_{ant}(i)$ the muscle activity of the antagonist muscle at each time point (i) of the gait cycle. The CCI(i) was calculated for each time point separately, as well as the mean value over full gait cycle. A CCI = 0 indicates no co-contraction and CCI = 1 indicates full co-contraction (Doorenbosch et al., 1995). It should be realised that there are many different methods to calculate a CCI and that there is no consensus on which calculation of the CCI is the most meaningful representation of co-contraction (Rosa et al., 2014). The reason we choose for this definition was because we found it meaningful for our study purpose. It yields zero when there is no co-contraction and one (i.e.100%) when both antagonists are equally active, expressed for each point in the gait cycle. It must be noted that such an equal amount of EMG (neurological co-contraction) does not mean that the resulting antagonistic joint moments cancel each other completely (mechanical co-contraction). This would require a complete other level of analysis. However, it does provide us insight in how the agonist and antagonist muscles are co-contracting at each time point of the gait cycle. Furthermore, the reliability of the CCI calculations are highly dependent on the reliability of the measured muscle activations. Therefore, we recommend, besides using standardized EMG placement protocols (Hermens et al., 2000), to always present the muscle activation patterns together with the CCI measures.

2.5. Perturbation response

Perturbation responses (PR) were calculated to capture the responses of the participant in the muscle activation patterns to the perturbations. The PR was calculated with the following equation (2) (Hobbelen and Wisse, 2007; van den Noort et al., 2017):

$$PR(i) = \sqrt{\left(\frac{\mu_p(i) - \mu(i)}{SD(i)}\right)^2} \tag{2}$$

The $\mu_p(i)$ represents the mean activation of a muscle at a certain time point (i) of the gait cycle during perturbed walking. For the same time point (i) the mean activation of the same muscle was calculated during unperturbed walking $\mu(i)$. The difference between the means ($\mu_p(i)$- $\mu(i)$) is divided by the standard deviation of the activation of the muscle at time point (i) during unperturbed walking. The absolute number that remains is the perturbation response PR(i) at time point (i). This number represents the variability of the selected muscle in response to a perturbation at a certain time point of the gait cycle relative to the naturally occurring variability during unperturbed walking. A higher perturbation response indicates more variability in the muscle activation caused by the perturbation.

2.6. Statistical analysis

Descriptive statistics were calculated of the muscle activation patterns during the different conditions (perturbation types and intensities). First, one-way repeated measures ANOVA were used to compare the mean values over full gait cycle of each muscle between perturbation intensities, independent of perturbation type. Second, the same test was used to compare between perturbation types, independent of intensity. Last, one-way repeated measures ANOVA were used to compare mean, peak and CCI values over full gait cycle between perturbation types per perturbation intensity. The Greenhouse-Geisser correction was used when the sphericity assumption was violated. Post-hoc pairwise comparisons (with Bonferroni correction) were used to determine the differences between each of the conditions.

Statistical parametric mapping (SPM) (Friston et al., 1994; Robinson et al., 2015) was used to compare the muscle activation patterns, CCI and PR at each point of the gait cycle between the different conditions (perturbation types, perturbation intensities and unperturbed gait). In SPM, a repeated measures ANOVA was used to determine the phases of gait that were statistically different between the conditions. The calculated mean values over these phases were compared using a repeated measures ANOVA test as described above. The significance level was $\alpha < 0.05$.

3. Results

3.1. The effect of perturbation intensity

3.1.1. Mean activation over full gait cycle

An increase of perturbation intensity presented a higher mean activation over full gait cycle in the RF, VL, ST, BF and LG muscles ($p < 0.05$, Fig. 2), independent of perturbation type. This difference was the largest between intensity 5 (I5) and intensity 1 (I1) with on average a difference of 2% mean activation ($p < 0.05$).

3.1.2. SPM analysis of muscle activation

As an example to show the effect of perturbation intensity on the knee joint muscle activation patterns, the responses to the DEC perturbation at five intensities is provided in Fig. 3. The SPM analysis of the other perturbation types presented similar results. In general, I5 of the DEC perturbation showed the largest deviations in muscle activation compared to the lower intensities. For example, in each of the quadriceps muscles a peak occurred around 30–40% gait cycle in response to the DEC perturbation at I4 or I5, which was different from the response to the DEC perturbation at I1, I2 ($p < 0.05$), but not from unperturbed walking ($p > 0.05$). Furthermore, a delay in the peak activation of the RF muscle was observed during the stance-swing transition (55–75% gait cycle) between I5 and unperturbed walking (length of delay: 3% of gait cycle, $p = 0.03$). The responses in the hamstring muscles were not different from unperturbed walking, but showed differences between the intensities in the ST muscle during 44–54% gait cycle and in the BF muscle during 81–95% gait cycle ($p < 0.05$, I5 compared to I1). Both gastrocnemius muscles showed a decrease in activation with increasing intensity around 15–40% gait cycle and an increase in activation after peak activation (47–57% gait cycle). Furthermore, a delay in peak activation of both gastrocnemius muscles was observed between I5 and unperturbed walking (length of delay 3% of gait cycle, $p < 0.05$).

3.1.3. SPM analysis of co-contraction patterns

The CCI of medial muscles was lower during 3–21% of gait cycle during the perturbed strides compared to the unperturbed strides ($p < 0.05$, Fig. 4), but post-hoc analysis did not present significant differences between intensities or unperturbed gait. The CCI of lateral muscles was similar between intensities and unperturbed gait. The CCI patterns of quadriceps vs. hamstrings presented differences during 3–12% and 19–22% of gait cycle between the intensities and unperturbed gait ($p < 0.01$). The post-hoc analysis showed that the CCI was lower during 3–12% of gait cycle during DEC perturbation at I4 (0.13, $p = 0.04$) and I5 (0.14, $p = 0.02$) compared to unperturbed gait.

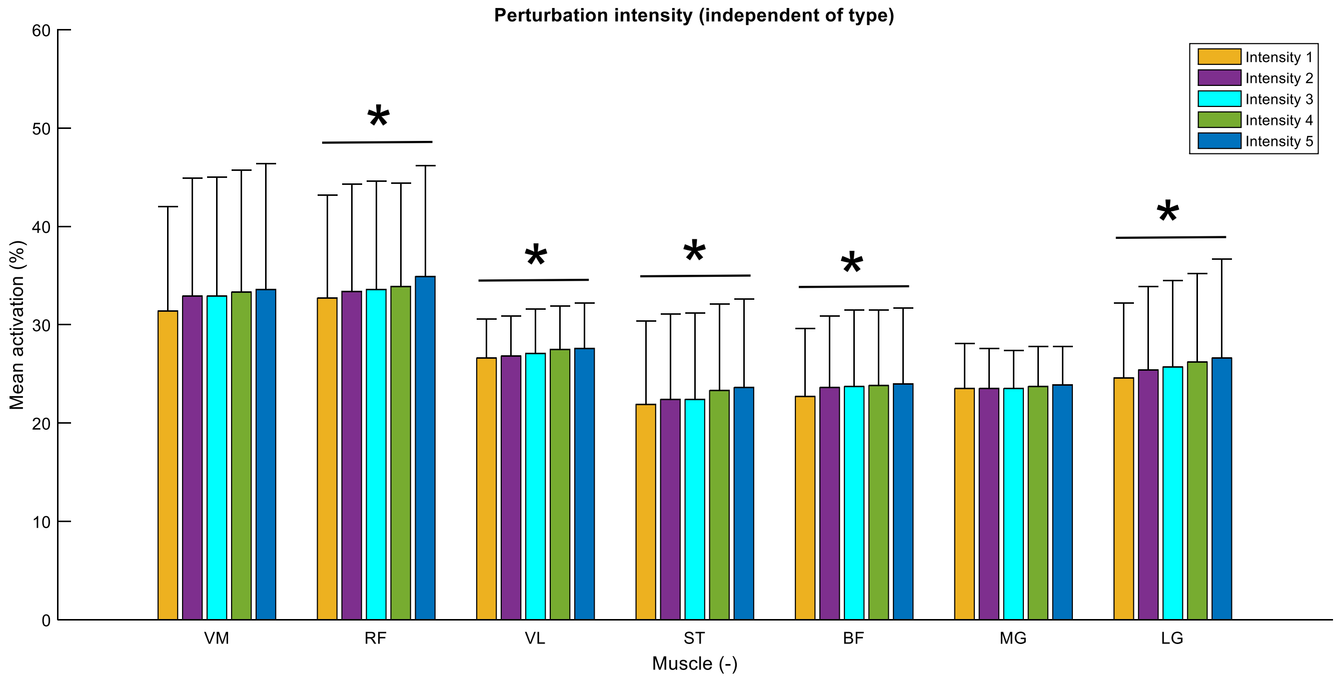

Fig. 2. *Effect of perturbation intensity on mean muscle activation during full gait cycle of each muscle, independent of type of perturbation. The asterisks above the bar plots show the significant differences between the conditions.* VM = Vastus medialis, RF = Rectus femoris, VL = Vastus lateralis, ST = Semitendinosus, BF = Biceps femoris, MG = Medial gastrocnemius and LG = Lateral gastrocnemius.

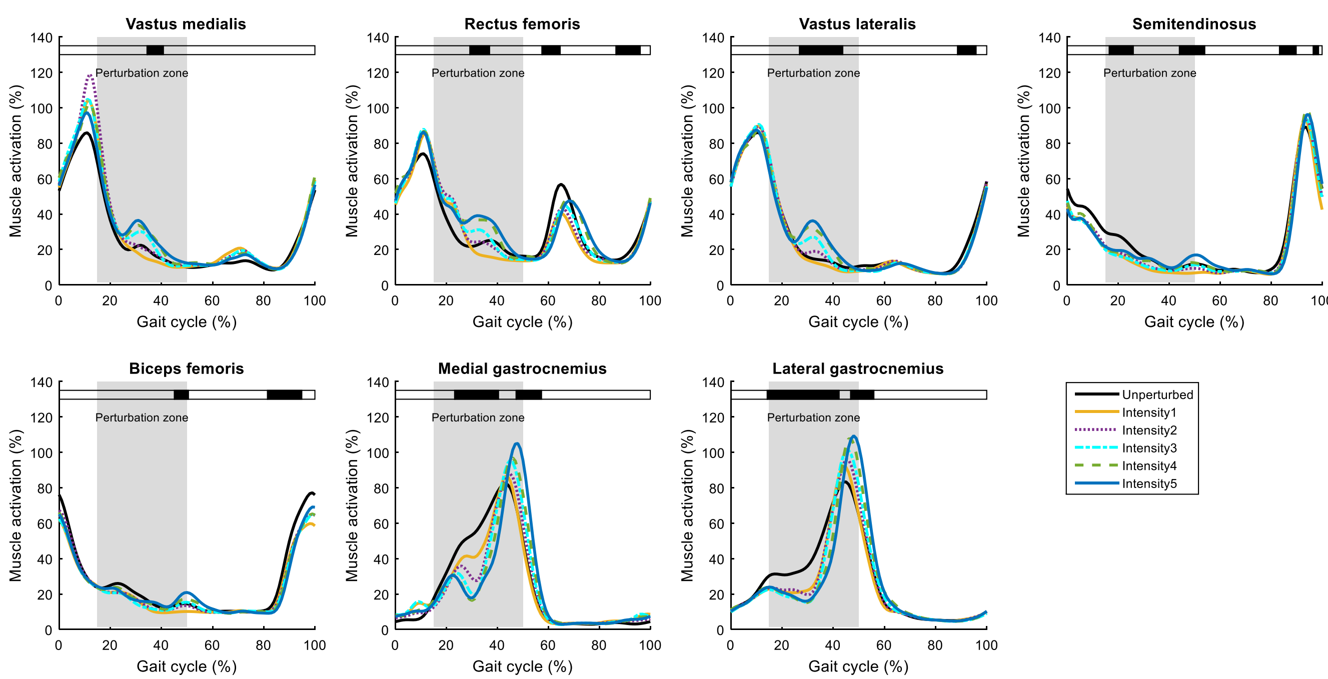

Fig. 3. Muscle activation patterns in response to the DEC perturbation at five different intensities, black = baseline, gold = I1, purple = I2 (dotted line), light-blue = I3 (dot-dash line), green = I4 (dashed line) and blue = I5. Rectangle above graph shows significant differences (black) or not (white) between the conditions following from the SPM results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1.4. *SPM analysis of perturbation responses*

The perturbation responses (PR) in general increased with an increase in perturbation intensity, which is mainly evident in the quadriceps muscles (Fig. 5). For example, the PR of the VL muscle increases during 31–37% of the gait cycle ($p = 0.01$, average value over gait phase: I1: 0.5, I2: 1.2, I3: 2.1, I4: 3.2 and I5: 4.0).

3.2. *The effect of perturbation type*

3.2.1. *Mean activation over full gait cycle*

In 3 of the 7 muscles (RF, BF and MG) differences in mean activation over full gait cycle were observed between the perturbation types ($p < 0.05$, Fig. 6), independent of perturbation intensity. The SR perturbation presented higher mean muscle activations in the RF muscle compared to all other perturbation types (MD of SR comparisons against all other

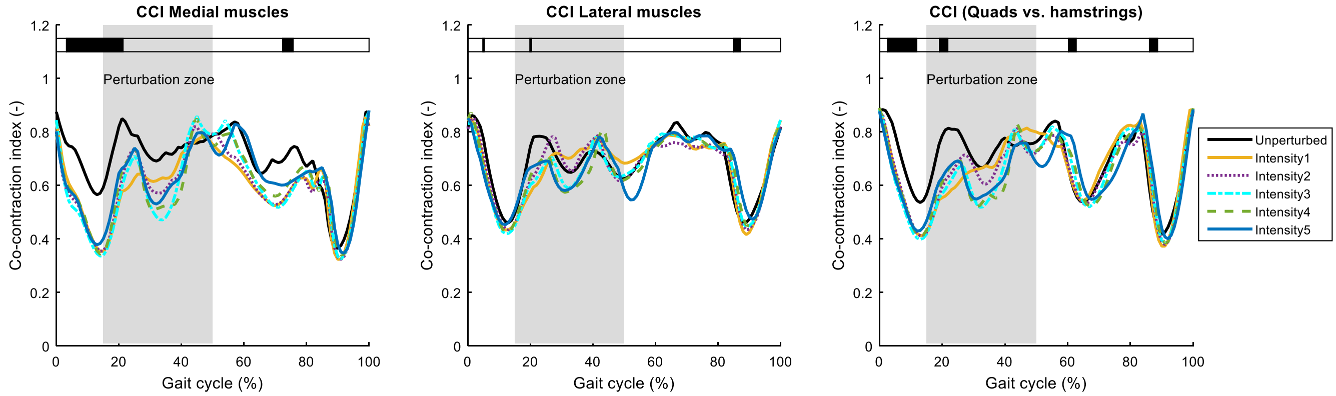

Fig. 4. Co-contraction indices of the medial muscles, lateral muscles and quads vs. hamstrings in response to the DEC perturbation at five different intensities, black = baseline, gold = I1, purple = I2 (dotted line), light-blue = I3 (dot-dash line), green = I4 (dashed line) and blue = I5. Rectangle above graph shows significant differences (black) or not (white) between the conditions following from the SPM results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

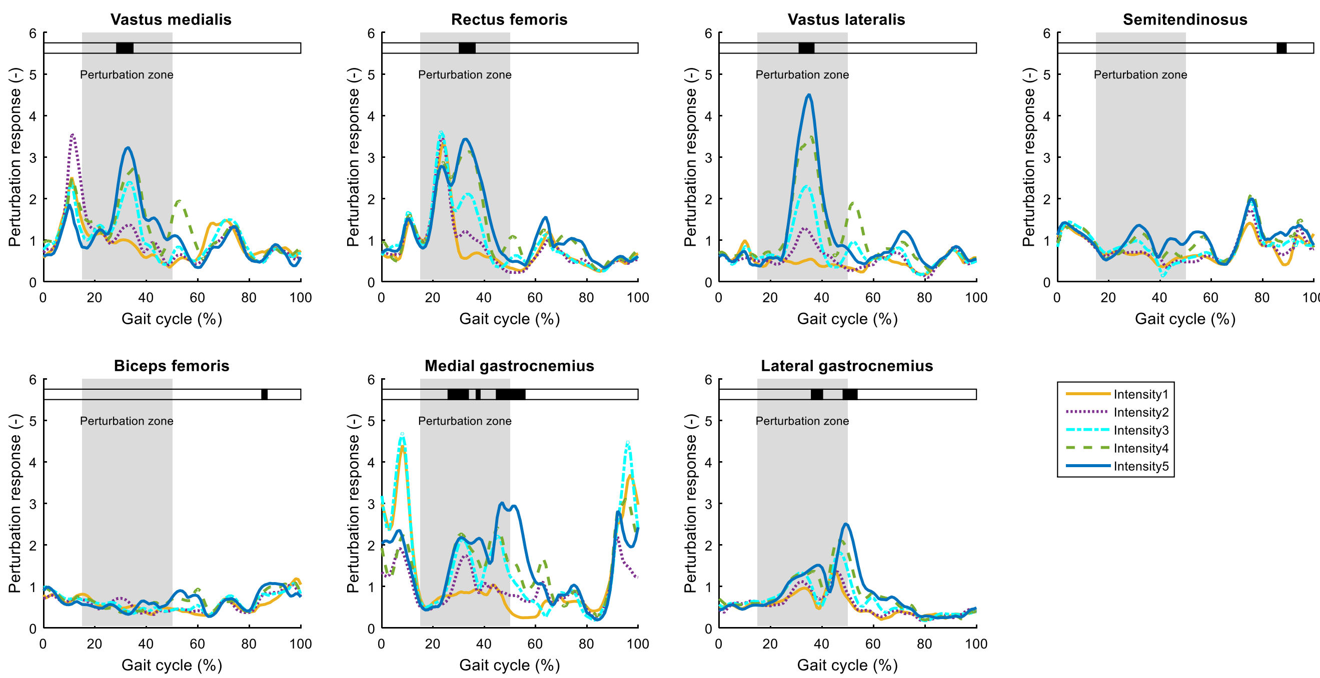

Fig. 5. Perturbation responses of the DEC perturbation at five different intensities, gold = I1, purple = I2 (dotted line), light-blue = I3 (dot-dash line), green = I4 (dashed line) and blue = I5. Rectangle above graph shows significant differences (black) or not (white) between the conditions following from the SPM results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

perturbations: 5%, $p < 0.01$). Furthermore, during ACC perturbation the mean muscle activation of the RF muscle was lower than during DEC (MD: 2%, $p < 0.01$) and SR perturbation (MD: 8%, $p < 0.01$). The mean activation of the BF and MG muscle were both higher during ACC and SL perturbation compared to the DEC (LH MD: 2%, $p < 0.01$, MG MD: 2%, $p < 0.01$) and SR perturbation (BF MD: 2% $p < 0.01$, MG MD: 1%, $p < 0.01$). The effect of perturbation type at each intensity on the mean muscle activation over full gait cycle can be found in supplementary table A (only significant differences) and is described in supplementary text A. The results below will be on the perturbation types at intensity 5, since the largest deviations from unperturbed gait were observed at this intensity (as described above).

3.2.2. SPM analysis of muscle activation

The effect of the different perturbation types at intensity 5 on the knee joint muscle activation patterns are shown in Fig. 7. A peak was present in each of the quadriceps muscles around 30–40% of gait cycle in response to the DEC perturbation, while the other perturbation types did not demonstrate this peak. The mean activation over this phase (30–40% of gait cycle) of the DEC perturbation was significantly higher in the RF muscle compared to the SL and SR perturbation and in the VL muscle compared to the SL perturbation. Different responses to the perturbation types were also observed in the RF muscle during the stance-swing transition. A higher RF peak activation was observed during SR perturbation compared to ACC (MD: 37%, $p = 0.01$) and SL perturbation (MD: 29%, $p = 0.05$). Furthermore, a delay in RF peak activation was observed during DEC (4% of gait cycle, $p = 0.02$) and SR (3% of gait cycle, $p = 0.03$) perturbations compared to unperturbed gait. Moreover, this difference in RF peak timing was also present between the ACC perturbation compared to the DEC (7% of gait cycle, $p = 0.01$) and SR perturbation (6% of gait cycle, $p = 0.04$). The activation of the ST was lower during 18–26% gait cycle of the ACC (MD: 11%, $p = 0.04$) and SL perturbations (MD: 11%, $p = 0.04$) compared to unperturbed walking. The peak activation of both hamstrings was not different from

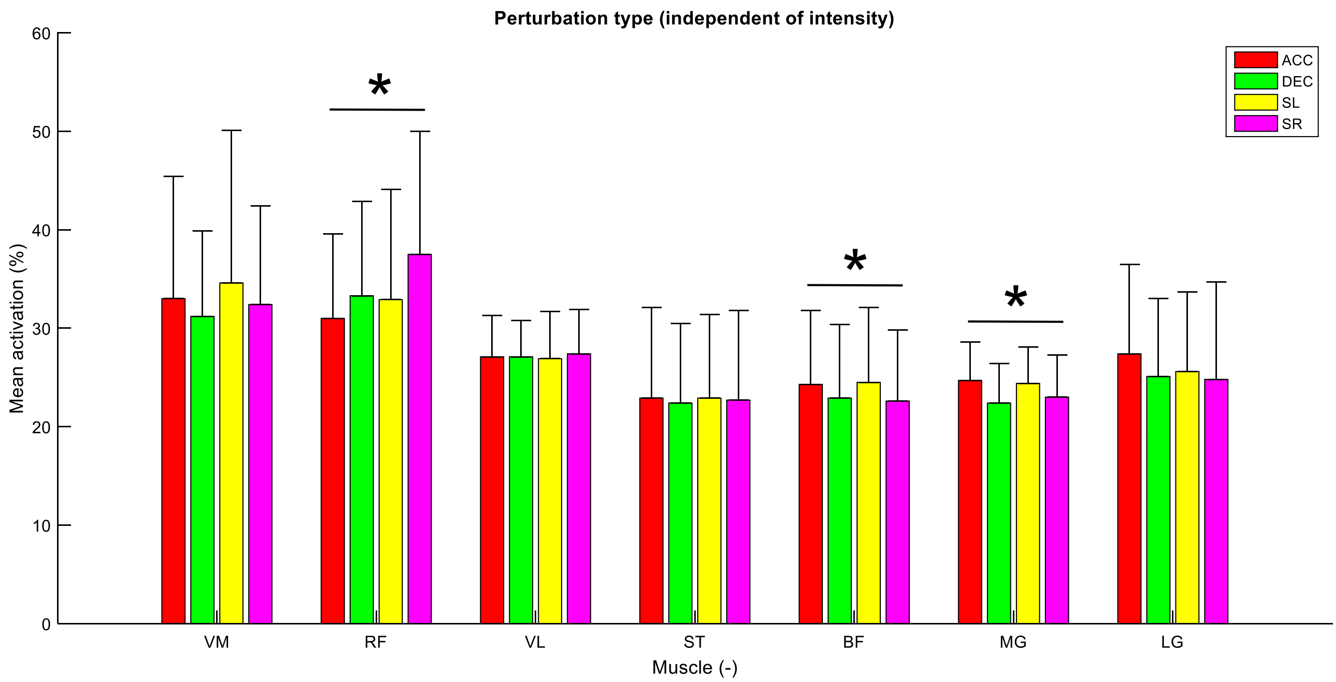

Fig. 6. *Effect of perturbation type on mean muscle activation during full gait cycle of each muscle, independent of perturbation intensity. The asterisks above the bar plots show the significant differences between the conditions.*ACC = Acceleration of one belt, DEC = deceleration of one belt, SL = Sway left, SR = Sway right, VM = Vastus medialis, RF = Rectus femoris, VL = Vastus lateralis, ST = Semitendinosus, BF = Biceps femoris, MG = Medial gastrocnemius and LG = Lateral gastrocnemius.

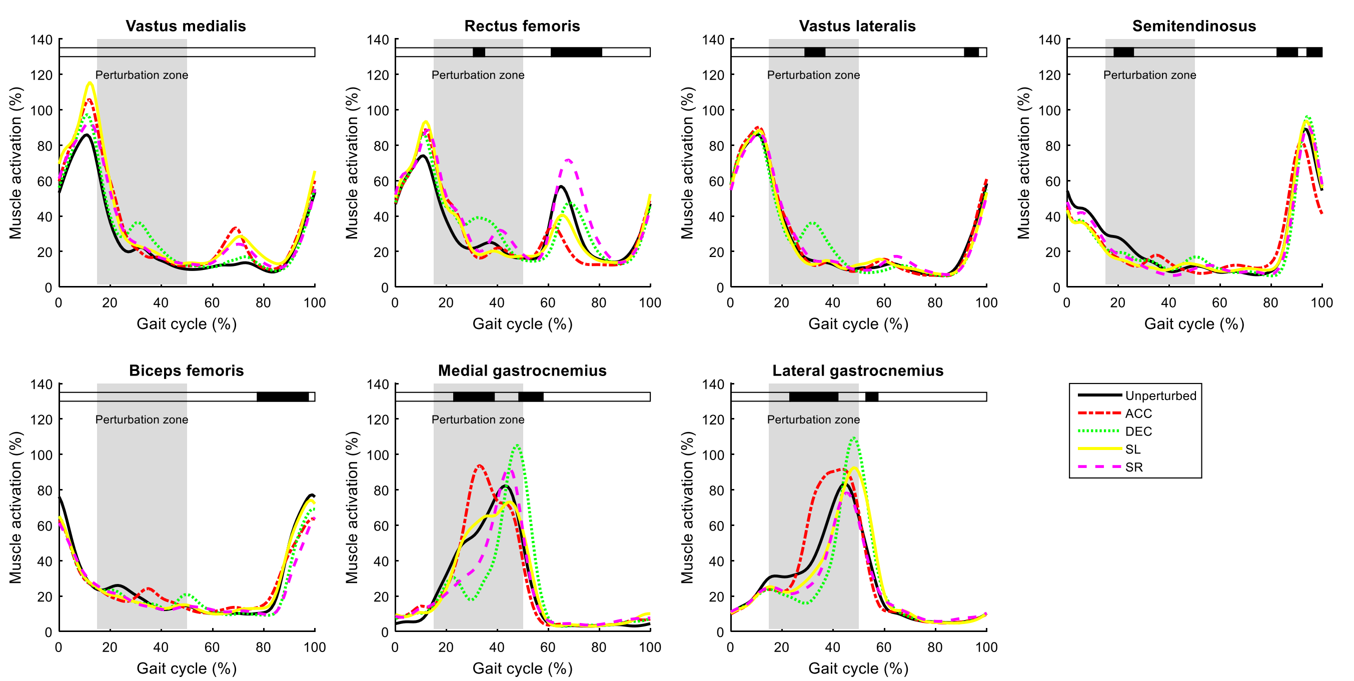

Fig. 7. Muscle activation patterns in response to all perturbation types at intensity 5, black = baseline, red = ACC (dot-dash line), green = DEC (dotted line), yellow = SL and magenta = SR (dashed line). Rectangle above graph shows significant differences (black) or not (white) between the conditions following from the SPM results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unperturbed walking or between types, except for a lower peak activation in the semitendinosus muscle observed during ACC perturbation compared to DEC perturbation (MD: 13%, $p = 0.04$). In the gastrocnemius muscles, a decrease in muscle activation was observed during 20–40% of gait cycle of the ACC perturbation versus an increase in muscle activation during the same time period of the DEC perturbation. Furthermore, an increase in activation of both gastrocnemius muscles was observed after peak activation in response to the DEC perturbation. Lastly, the timing of the peak activation of the gastrocnemius muscles differed between the ACC and DEC perturbation (MG: 14% of gait cycle, $p < 0.01$, LG: 8% of gait cycle, $p = 0.03$)

3.2.3. SPM analysis of co-contraction patterns

A lower CCI of medial muscles was observed during 3–22% of gait cycle in response to the ACC perturbation (MD: 0.24, $p = 0.02$) and the SL perturbation (MD: 0.23, $p = 0.05$) compared to unperturbed gait

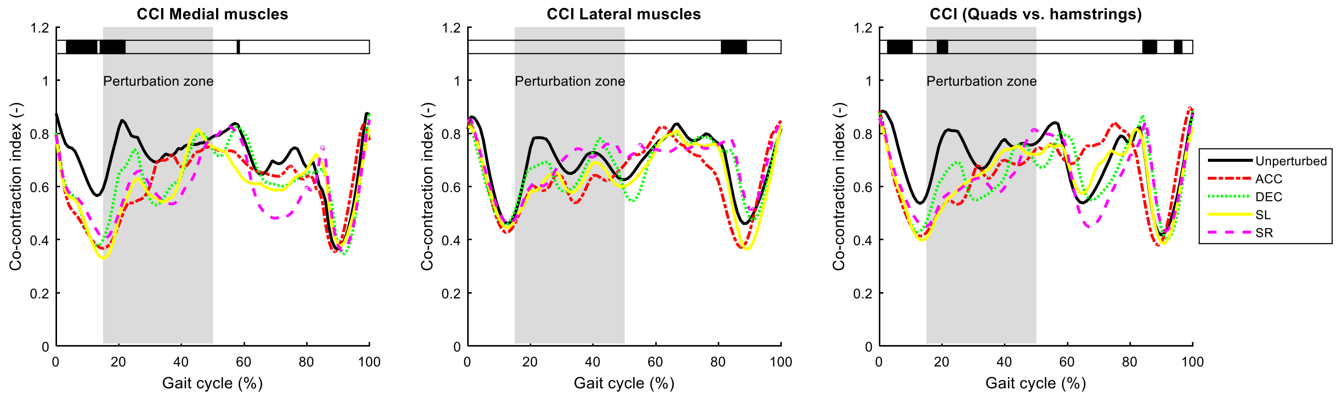

Fig. 8. Co-contraction indices of the medial muscles, lateral muscles and quads vs. hamstrings in response to the perturbation types at intensity 5. Black = baseline, red = ACC (dot-dash line), green = DEC (dotted line), yellow = SL and magenta = SR (dashed line). Rectangle above graph shows significant differences (black) or not (white) between the conditions following from the SPM results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 8). The SPM analysis of the CCI of lateral muscles presented no differences between the perturbation types or unperturbed gait during the stance phase. The CCI of quadriceps vs. hamstrings presented differences during 3–10% and 18–22% of gait cycle. During 3–10% of gait cycle a lower CCI was observed in the ACC (MD: 0.15, $p = 0.02$), DEC (MD: 0.14, $p = 0.01$) and SR (MD: 0.11, $p = 0.05$) perturbation types compared to unperturbed gait. During 18–22% of gait cycle the post-hoc analysis did not present differences between the perturbation types or unperturbed gait.

3.2.4. *SPM analysis of perturbation responses*

Fig. 9 presents the comparison of the PR of the perturbation types at intensity 5. The PRs are in general similar between the perturbation types, except for the DEC perturbation during 30–45% of gait cycle in the RF and VL muscle and the ACC and DEC perturbation in the medial gastrocnemius.

4. Discussion

The aim of this study was to compare the responses in knee joint muscle activation patterns to different types and intensities of perturbations during gait in healthy subjects. Increasing the perturbation intensity resulted in a higher mean activation over full gait cycle in five of the seven muscles of the knee. Moreover, higher PRs were observed with increasing perturbation intensity. A different type of perturbation presented a different response in some muscles, mainly in the rectus femoris during terminal stance and the stance-swing transition, and during push-off in the gastrocnemius muscles. The PRs were overall similar between the types of perturbations, except for the DEC perturbation during terminal stance in the RF muscle and VL muscles and for the ACC and DEC perturbation in MG muscle. Lastly, the participants had lower co-contraction of the thigh muscles just before perturbation compared to the same gait phase of unperturbed gait.

Participants showed small changes in their knee joint muscle

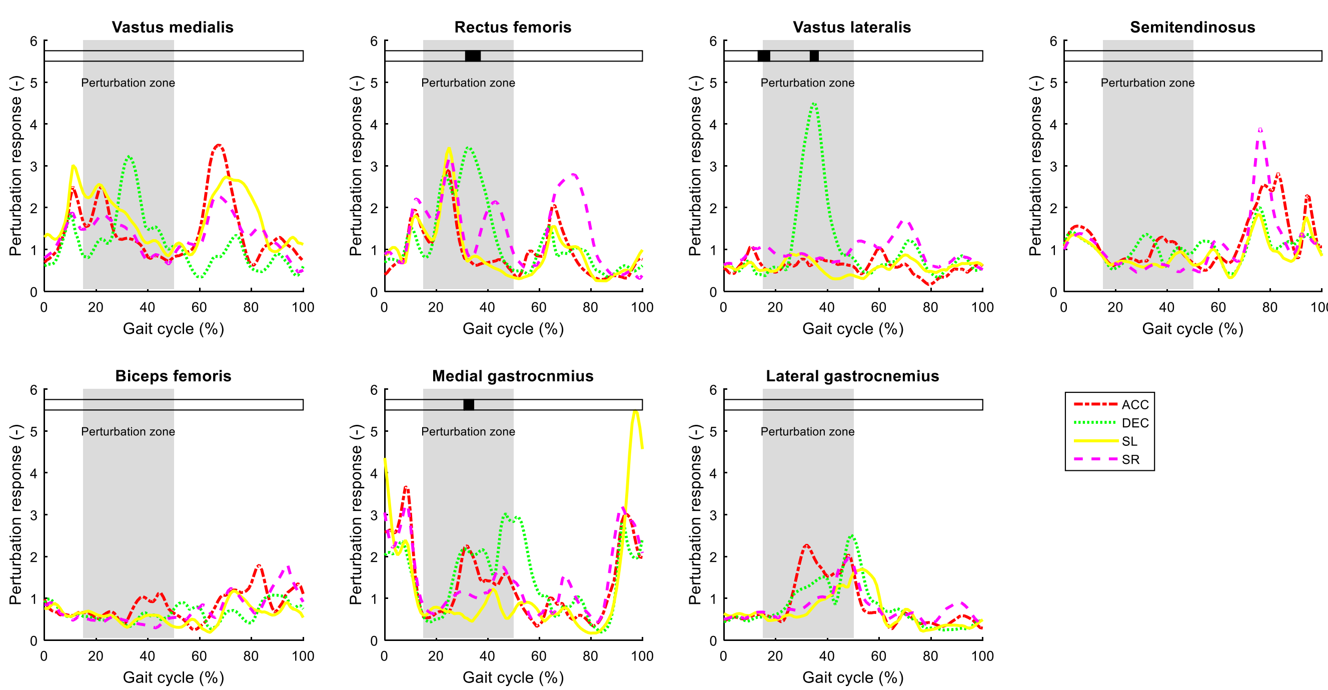

Fig. 9. Perturbation responses of the perturbation types at intensity 5, red = ACC (dot-dash line), green = DEC (dotted line), yellow = SL and magenta = SR (dashed line). Rectangle above graph shows significant differences (black) or not (white) between the conditions following from the SPM results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

activation patterns, suggesting that only minor adaptations were needed to respond to the different perturbations. First of all, as expected, the participants gradually increased their muscle activation in response to an increase of the intensity of the perturbation. This was also observed in the calculated perturbation responses (PR) of the muscle activation patterns. A study by van den Noort et al. 2017 (van den Noort et al., 2017), using the same dataset, observed a similar increase in calculated perturbation responses of knee angles with increasing perturbation intensity during SL and SR perturbation (ACC and DEC were not included in this study). This demonstrates that a higher perturbation intensity is more effective in provoking a response in both the knee joint muscle activation, as well as in the knee angles as shown in the study by van den Noort et al 2017. Although this seems obvious, the question remains at which intensity the participants would have been unable to counteract the perturbations with subtle responses, and would need large adaptations in muscle activation to prevent falling. Using different perturbation types resulted in differences in the muscle activation patterns of the gastrocnemius muscles and rectus femoris muscles. In general, the ACC and DEC perturbations showed opposite responses in these muscles. For example, the timing of the peak activation of the rectus femoris during the stance-swing transition for the ACC perturbation was 3% of gait cycle earlier than unperturbed gait, while for the DEC perturbation this was 4% of gait cycle later. This could possibly be explained by a longer stance time during DEC perturbation that was observed in the study by Sloot et al. (Sloot et al., 2015), which used the same gait datasets. Lastly, the participants had lower co-contraction indices just before the start of the perturbation. This might be a strategy of healthy young subjects to prepare themselves for the perturbations during gait. Such a similar strategy was observed in a study by Oliveira et al. (Oliveira et al., 2013) in healthy participants, but then during loading response of a perturbed cutting manoeuvre. Investigation of the strides in-between perturbations could reveal whether subjects prepare themselves before perturbation and whether they learn to do so after experiencing several perturbations.

4.1. Future directions

The responses observed in the participants of this study provide a baseline to compare responses from other populations against. In other words, to study possible aberrant muscle activation in response to different perturbations in older adults or patients with knee disorders. This could provide information on how the muscle activation around the knee changes with age and with different knee disorders. Besides this, perturbations during gait could be further explored, since the literature on this is scarce. For example, intensity, duration, timing of the perturbation could be investigated to ultimately find the perturbation that is able to best reveal impairments in muscle activation around the knee of patients with knee disorders.

This study has some limitations. Firstly, walking in a gait laboratory on a treadmill in a virtual reality environment with perturbations is different from walking (with natural occurring perturbations) in real life. However, it enables us to safely investigate perturbations during gait in a controllable and repetitive manner. Secondly, the intensity of the perturbations could have been larger to possibly evoke larger responses in the muscles. However, care should be taken with increasing the intensity of the perturbation, since it is unknown what the maximum intensity of perturbation is that the participant can respond too (lead to fall or injury). Thirdly, firm conclusions could not be drawn from the results of this study due to the small sample size. Nevertheless, the results of this study could provide research directions for future studies with larger sample sizes. Fourthly, leg dominance was not assessed during the measurement. Therefore, some participants might have performed better than other participants in responding to the perturbations. The reason we have chosen to select the right leg of each participant to be perturbed was to keep the direction of SL and SR perturbation constant between participants.

5. Conclusion

Subtle changes in knee joint muscle activation patterns were observed in response to different types and intensities of perturbations during gait in healthy subjects. The highest intensity we used provokes the largest response in muscle activation and we observed some muscle specificity to different types of perturbation. The results of this study provide insights regarding how the muscles are activated to stabilize the knee and drive knee function while being exposed to different perturbations during gait. Furthermore, it could guide future studies investigating pathological knee function (e.g. knee joint instability) in determining aberrant muscle activation and therewith enable development of treatments to improve muscle activation in patients with knee disorders.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2021.102572.

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