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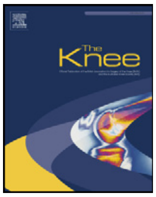

Effect of walking with a modified gait on activation patterns of the knee spanning muscles in people with medial knee osteoarthritis

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ABSTRACT

Objective: To evaluate muscle activation patterns and co-contraction around the knee in response to walking with modified gait patterns in patients with medial compartment knee-osteoarthritis (KOA).
Design: 40 medial KOA patients walked on an instrumented treadmill. Surface EMG activity from seven knee-spanning muscles (gastrocnemius, hamstrings, quadriceps), kinematics, and ground reaction forces were recorded. Patients received real-time visual feedback on target kinematics to modify their gait pattern towards three different gait modifications: Toe-in, Wider steps, Medial Thrust. The individualized feedback aimed to reduce their first peak knee adduction moment (KAM) by ≥10%. Changes in muscle activations and medial/lateral co-contraction index during the loading response phase (10–35% of the gait cycle) were evaluated, for the steps in which ≥10% KAM reduction was achieved.
Results: Data from 30 patients were included in the analyses; i.e. all who could successfully reduce their KAM in a sufficient number of steps by ≥10%. When walking with ≥10% KAM reduction, Medial Thrust gait (KAM −31%) showed increased flexor activation (24%), co-contraction (17%) and knee flexion moment (35%). Isolated wider-step gait also reduced the KAM (−26%), but to a smaller extent, but without increasing muscle activation amplitudes and co-contraction. Toe-in gait showed the greatest reduction in the KAM (−35%), but was accompanied by an increased flexor activation of 42% and hence an increased co-contraction index.
Conclusion: Gait modifications that are most effective in reducing the KAM also yield an increase in co-contraction, thereby compromising at least part of the effects on net knee load.

1. Introduction

Gait retraining shows promise as a new treatment to reduce knee joint loading in knee osteoarthritis (KOA) aiming to slow down the rate of disease progression [1–5]. The intervention assumes that knee joint overloading, especially at the medial compartment during gait is an important cause of progression of KOA [2]. It targets the distribution of force between the medial and lateral compartments of the tibiofemoral joint. This distribution depends on two main, partly dependent, factors [6]: the mag-

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nitude of the external knee adduction moment (KAM) [7] and the magnitude of muscle forces to support coordination and stability of the knee [8].

Although many studies have shown that gait retraining is effective in reducing the KAM, the influence of changes in muscle activation, an important determinant for knee joint loading, is often neglected in these studies [1,9,10]. From electromyography (EMG)-driven modeling studies it is known that muscle forces have a major contribution to knee joint loading [6,11,12]. Internal knee joint loading will be increased by co-contracting muscles without affecting the value of the net external moment [13,14]. This is because concurrent activation of agonist and antagonist muscles will cancel out each other's contribution to the joint moment, but add in their contribution to the knee reaction force [15]. While co-contraction will enhance stabilization of the knee joint, it increases knee loading, which is not reflected by the KAM [9]. In fact, increased magnitude and duration of co-contraction on the medial side of the knee joint are associated with increased medial contact forces and cartilage volume loss in the medial compartment [8,14]. Consequently, muscle co-contraction is an important outcome parameter that should be considered in interventions that target KOA progression such as gait retraining.

Several gait modifications are known to be associated with a reduction of the magnitude of the first peak of the KAM, which in turn is associated with disease progression [16]. Especially, Toe-in, Medial Thrust gait and walking with Wider Steps have been shown to be effective for reducing the KAM [10,17,18]. Another strategy shown to be effective is trunk lean, but it has serious drawbacks, i.e. an increased energy cost of walking and potentially harmful through increased loading in the lower back [17,19].

Little is known about how muscle activation patterns change as a result of gait retraining. We identified six studies that investigated muscle activation changes during gait retraining [20–25]. These studies focused on changing the foot progression angle, of which four studies taught participants Toe-in gait [22–25], while the other two focused on toe-out gait [20,21]. Toe-in gait showed an increased medial hamstring activation during stance, higher co-contraction between the lateral [25] and medial [24] quadriceps and hamstrings and a trend of higher medial to lateral hamstring activity. There was a high variability in the change in muscle activation between participants when adopting a Toe-in gait [23,24], possibly related to the method of the gait retraining [22,24]. It was argued that this increased co-contraction is related to the novelty of the gait pattern [25,26].

However, an important limitation in the above studies is the absence of individualization. These Toe-in studies used a fixed foot progression angle or amount of angular change that might have induced a variety of response, since recent studies emphasize the need for individualization of gait retraining, to account for individual differences [10,23–25,27]. Another limitation of the previous studies is that, while they evaluated gait retraining aimed to reduce the KAM, actual information on the KAM was absent [20–24]. Therefore, these studies may have been analyzing a gait pattern that did not reach the goal of reducing KAM. When KAM was calculated retrospectively, the first peak of the KAM had indeed not reduced for all participants [22,25]. No studies that investigated muscle activation changes in response to applying Wider Steps and Medial Thrust gait were found.

The aim of this study is to evaluate the effect of three individualized gait modification strategies (Toe-in, Wider Steps and Medial Thrust gait) on muscle activation patterns around the knees in patients with medial KOA. We hypothesize that the frontal net knee moment (the KAM) will be reduced, but muscle co-contraction will be increased.

2. Methods

2.1. Study design

In this study post-hoc analyses were performed of a cross-sectional experimental trial.

2.2. Participants

Forty patients with medial KOA were recruited through advertising in local newspapers and an e-magazine, and from a local rehabilitation centre (Reade, Center for Rehabilitation and Rheumatology, Amsterdam, the Netherlands). Inclusion criteria were a clinical diagnosis of KOA [28], age between 50 and 75, and the ability to walk unaided for at least 30 min. Exclusion criteria were predominant lateral or patella-femoral osteoarthritis, previous or planned hip or knee replacement, hip or ankle arthritis, rheumatoid arthritis and BMI > 35. Approval was obtained from the VUmc Medical Ethical Committee. All participants provided their written informed consent.

2.3. Gait analysis

Patients attended the Virtual Reality Lab at the Amsterdam University Medical Centers, location VUmc for a single measurement session on the GRAIL system (MotekForce Link B.V. Amsterdam, NL), consisting of a dual-belt instrumented treadmill, a motion capture system and a semicircular screen for real-time feedback. A detailed description of the gait modification intervention and the collection and analysis of the kinematic and kinetic data were reported by Richards et al. [29] and summarized below.

After familiarization to the treadmill of at least three minutes, the comfortable walking speed was determined for each patient. This walking speed was set for all four three-minute gait trials, i.e. Baseline, Toe-in, Wider Steps and Medial Thrust. A baseline trial was collected to measure the natural gait pattern of the participants. During Toe-in, Wider Steps and Medial Thrust trials the participants trained these three different gait modifications, receiving specific instructions [29] focusing on the most symptomatic side. Feedback on target kinematics were provided on the 180° semicircular screen (see Figure 1). The size of the modifications (degrees of foot internal rotation (Toe-in), distance along the frontal axis between the feet (Wider Steps) and between the

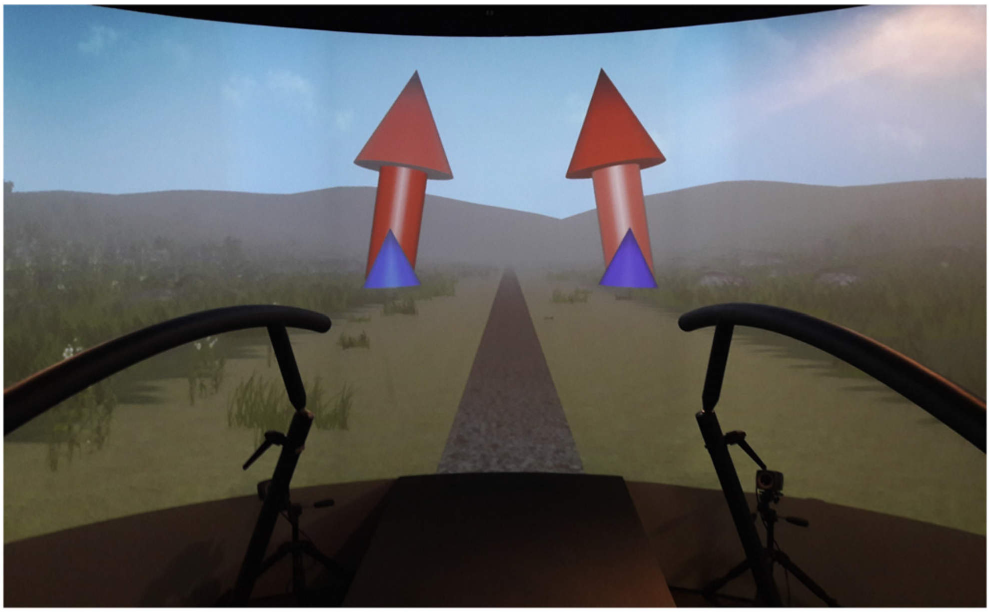

Figure 1. Experimental set up: Treadmill with a screen providing kinematic feedback. On the screen feedback on the foot progression angle (FPA) is provided (Toe-in trial). The large arrows are the target FPA, the small blue arrows represent the feet in real-time. The color of the large arrows change from red (more than 5 degrees error of FPA), orange (2.5 to 5 degrees error of FPA) and green (within 2.5 degrees of the correct FPA).

knees (Medial Thrust)) was individualized, based on data from previous trials. From the gait retraining trials, the last 90 s was analyzed.

Kinematic data were collected at 100 Hz, using a 10-camera motion capture system (Vicon, Oxford Metrics Group, Oxford, UK). At a sample rate of 1000 Hz, forces were recorded from two force plates within the treadmill (MotekForceLink B.V., Amsterdam, NL). Reflective markers were placed on the lower limbs and trunk based following recommendations of the International Society of Biomechanics (ISB) for 3D motion capture of the lower limbs [30]. Electromyographic (EMG) data were recorded at 1000 Hz, using a wireless surface EMG system (Zerowire Cometa Systems, Italy). Muscle activation data were obtained for seven muscles spanning the most affected knee: Vastus Lateralis (VL), Rectus Femoris (RF), Vastus Medialis (VM), Lateral and Medial Hamstrings (LH, MH), Lateral and Medial Gastrocnemius (LG, MG). Electrode placement was determined using Seniam guidelines and local protocol. Raw EMG signals were high pass filtered at 20 Hz, full-wave rectified and low pass filtered at 6 Hz using 2nd order bi-directional Butterworth filters [31].

For the analyses of the baseline trial all gait cycles were included, except for the steps in which the stance foot was placed on the contralateral force plate. For the following three trials only those steps for which KAM was reduced sufficiently were included in the analyses. If less than 10 steps reached the target KAM reduction of 10%, that gait pattern was considered not suitable for that participant, so that trial was excluded from the analysis.

To determine the magnitude of applied gait modifications, spatial parameters were calculated: foot progression angle (foot segment angle in the transverse plane when the foot was flat on the ground), step width (difference in ankle joint center along the frontal axis between left and right initial contacts) and inter-knee distance (mean difference in knee positions along frontal axis during double stance). EMG was amplitude-normalized to the maximal value during the baseline gait trial. The KAM, knee flexion moment (KFM), activation of all muscles and the co-contraction were calculated by taking the mean over 10 to 35% of the stance phase (i.e. the time interval around first peak of KAM which is the same window as used for feedback). Co-contraction between lateral and medial knee spanning muscles was calculated as the co-contraction index (CCI) [32]. The CCI was defined based on the sum of the medial (MG, MH, VM) and the sum of the lateral muscles (LG, LH, VL) at the time interval around first peak of KAM (Eq. (1)).

$$\mathrm{CCI} = \int_{i=10}^{35} \frac{\text{lower EMG}_i}{\text{higher EMG}_i} \text{ x } (\text{lower EMG}_i + \text{higher EMG}_i) \tag{1}$$

In the above equation of the CCI, the *lower EMG* is the activity of the muscle group (either medial or lateral) with the lower level of summed activity and the *higher EMG* is the activity of the muscle group with the higher level of summed activity.

All kinematic [33,34], kinetic [35] and co-contraction index [36] outcome measures of this study have shown to be reliable on between day measurements. Given the within-subject and session analyses used in our study, conditions were compared with an even higher reliability.

2.4. Statistical analysis

Descriptive statistics were used to characterize the study population. Prior to statistical analysis, outcome measures were assessed for normality with histograms and Shapiro–Wilk tests. Differences between the baseline trial and the three gait modification trials were assessed with regard to spatial parameters, muscle activation amplitudes and the CCI for the feedback leg only, using within-subject, paired t-tests with Greenhouse–Geisser correction applied as required. Bonferroni adjustments were made to correct for the number of tests. All analyses were performed using SPSS software, version 22.0 (SPSS, Chicago, IL, USA) with $\alpha = 0.05$.

3. Results

Of the 40 participants in this study, 30 managed to reduce their first peak of KAM in more than 10 strides in at least one of the conditions (mean 52, range 11–88 strides) of the maximal 94 strides available per trial. Table 1 shows the demographics of all patients who were included in the analyses. Of these 30 participants 27, 22, and 28 participants reduced their KAM in at least 10 strides during the Toe-in, Wider Steps and Medial Thrust conditions respectively and were therefore included in the analyses of these conditions (Table 2).

Reducing the KAM by at least 10% required significant changes in the gait patterns, which was reached in a similar amount of steps during the different gait conditions (Table 2). During both the Toe-in and Medial Thrust conditions the participants turned their feet significantly more inwards by seven and five degrees ($p < .001$), respectively. Step width was significantly increased in all conditions, ranging from 0.03 to 0.08 m ($p < .001$). The inter-knee distance increased by 0.05 m during the Wider Steps condition ($p < .001$) and did not change during Toe-in and Medial Thrust condition. Reduction of the KAM was greatest during the Toe-in condition (−46%, $p < .001$). During the Wider Steps condition the KAM reduced less than during Toe-in (−33%, $p < .001$). Medial Thrust showed similar changes as Toe-in with a decrease of the KAM of −43% ($p < .001$), but a strong increase of the KFM (35%, $p = .007$). See Figure 2 for a visualization of the changes in KAM between the conditions.

Paired t-tests revealed significant differences in average muscle activation in the area of the first peak of KAM in the hamstrings and gastrocnemius muscles in two conditions (Figure 3, Table 3). The Toe-in and Medial Thrust conditions demonstrated an increase of the activation of the lateral and medial hamstrings by 29% and 61% (Toe-in) and 26% and 42% (Medial Thrust) and of the lateral and medial gastrocnemius by 46% and 33% (Toe in) and 15% and 11% (Medial Thrust), respectively ($p < .01$) (Table 3). The Toe-in condition also showed a significant decrease of Vastus Lateralis activation ($p = .013$). Wider Steps showed no significant changes in muscle activation. The average CCI between the lateral and medial muscles was significantly increased in the Toe-in and Medial Thrust conditions ($p < .01$), while the CCI did not change during the Wider Steps condition (Table 3).

4. Discussion

The three investigated gait modifications (Toe-in, Wider Steps, Medial Thrust) had different effects on muscle activation patterns around the knee, when performed with at least 10% KAM reduction during each step compared to the natural gait of the participants. This study showed that the use of Wider Steps to reduce the KAM is effective (reduced KAM by ≥10%) in 22/40 patients and was not accompanied by significant changes in the activations of the knee spanning muscles. In addition, the CCI was not increased when walking with Wider Steps. Walking with Toe-in gait led to the greatest reduction of KAM (−46%), but increases were mainly seen in muscle activations of the gastrocnemius and hamstrings muscles and in co-contraction. Walking with Medial Thrust was accompanied with increases in muscle activation, co-contraction and peak KFM.

The effect on muscle activations around the knee of increased step width during walking has not been investigated before. Considering muscle activation changes, Wider Steps was the most successful gait modification. Wider Steps did not lead to increases in muscle activation or co-contraction, implying no confounding increase of knee joint loading was shown. Wider Steps may increase the activation of the hip abductor muscles, which were not recorded in this study. Of these abductors, only the

Table 1
Demographics. Mean (SD).

Sample size (n)	30
Age (years)	62.7 (5.9)
Gender, female (n)	16
BMI (kg/m^2)	25.5 (2.7)
Mass (kg)	77.1 (12.1)
KL-score (n)	KL1: 12 KL2: 7 KL3: 7 KL4: 4
Gait velocity (m/s)	1.1 (0.2)

Table 2
Kinematics and kinetics. Mean (SD).

	Baseline	Toe-in	p	Wider Steps	p	Medial Thrust	p
# participants (N)	30	27		22		28	
# successful steps (mean (range))	63 (10–84)	47 (11–87)		45 (12–79)		51 (11–88)	
Foot progression angle (deg)[a]	−4.12 (4.80)	**3.25 (4.80)**	0.000	−3.88 (4.60)	0.276	**0.49 (5.10)**	0.000
Step width (m)	0.16 (0.03)	**0.20 (0.03)**	0.000	**0.24 (0.04)**	0.000	**0.19 (0.04)**	0.000
Inter-knee distance (m)	0.18 (0.03)	0.19 (0.03)	0.097	**0.23 (0.03)**	0.000	0.19 (0.03)	0.476
1st peak KAM(%BW*Ht)	2.48 (1.01)	**1.61 (0.93)**	0.000	**1.84 (0.83)**	0.000	**1.69 (1.00)**	0.000
KFM peak (%BW*Ht)	1.70 (3.15)	1.61 (3.41)	0.458	1.24 (3.52)	0.457	**2.39 (3.46)**	0.007

Bold numbers are significant different from baseline; p < .05.

[a] Negative values represent an external foot progression angle.

tensor fascia latae crosses the knee joint, which may not have a great impact on knee joint loading, considering its low strength [37]. Furthermore, in terms of the number of steps reaching the target KAM reduction of 10%, we saw that walking with Wider Steps was equally as feasible as walking with Toe-in gait.

While the Toe-in condition was accompanied with the largest reduction in the KAM, muscle activation of the flexor muscles were increased by 42%. In this study we only analyzed the steps with at least 10% reduction of the first peak of KAM. Although that gave certainty that only valid, i.e. effective, steps were analyzed, we got similar results as studies that did not take real-time calculations of the KAM reduction into account [24,38]. Those studies found a trend towards an increased medial-lateral hamstring ratio when patients with medial KOA internally rotated their feet during gait [22,24], which corresponds to our findings. During the Toe-in condition, two unfavorable muscle activation changes occurred, as reflected by the increased CCI; total amount of muscle activation increased and the medial hamstring activation increased more than the lateral, being similar to what was

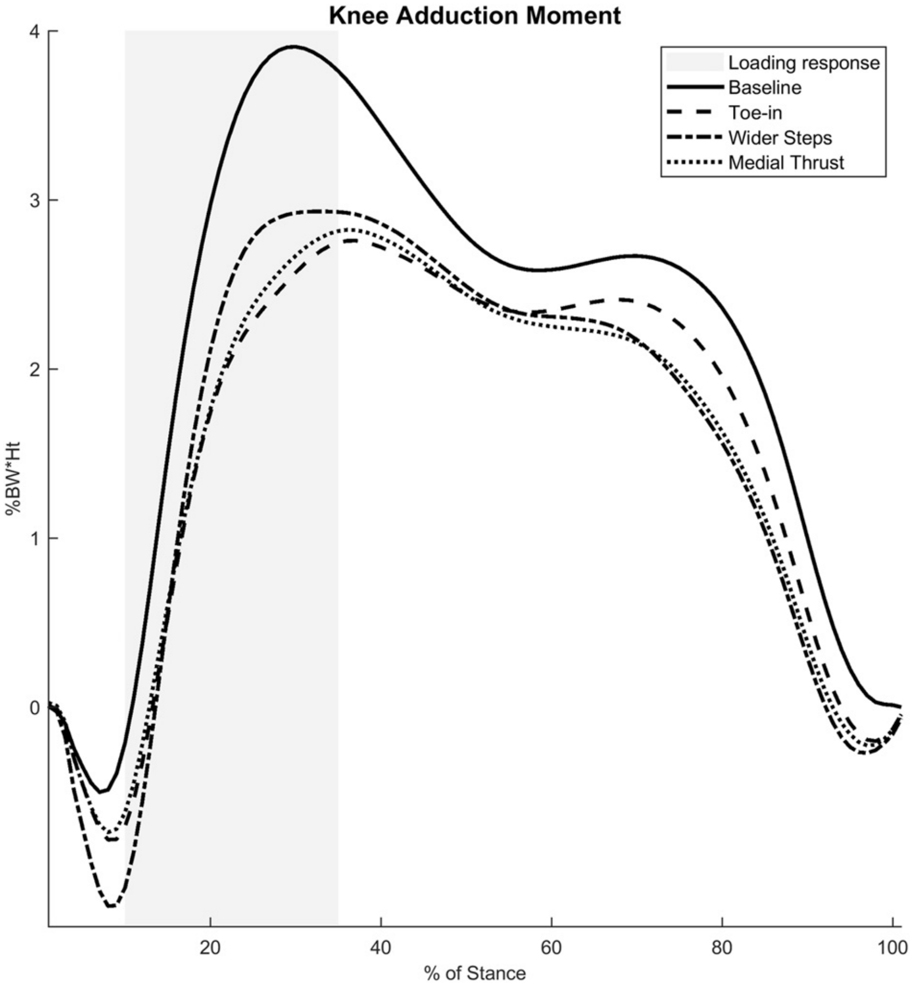

Figure 2. Group average Knee Adduction Moment per condition. Analyses were performed over the loading response (gray area).

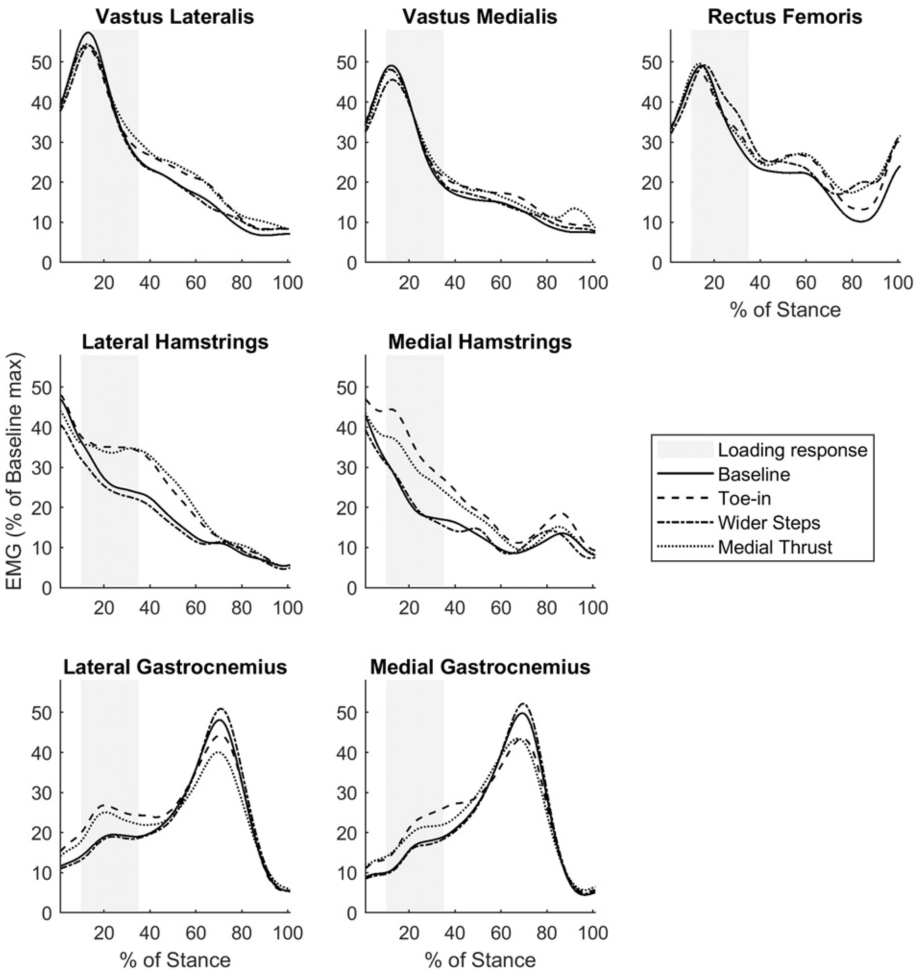

Figure 3. Group average EMG activations per condition. Analyses were performed over the loading response, this is the phase in which the first peak of KAM occurs (gray area).

found by Charlton et al. [24]. This may be related to the attachment sites of the medial hamstrings, which gives them the capacity to internally rotate the femur [39], which is necessary to achieve a Toe-in gait pattern.

When participants attempted to walk with Medial Thrust, they showed a highly variable performance. While the instruction was to minimize increase in step width, a significant increase in step width occurred. This may have concealed a reduction in inter-knee distance. Despite clear instructions provided by the researcher, this gait pattern was experienced as the most difficult as reported by the participants and as seen by the absence in reduction in inter-knee distance between the stance knee and contralateral knee. These findings question the clinical feasibility of such gait modification. Post-hoc analyses revealed that Toe-in and Wider Step conditions showed a greater reduction of varus knee angle during early stance than Medial Thrust condition. The

Table 3
Muscle activation amplitudes and Co-Contraction Indices (CCI). Values displayed as: mean (standard deviation)
Muscle activations are expressed as percentage of the maximum during baseline walking and calculated over 10–35% of the stance phase.

	Baseline	Toe-in	p	Wider Steps	p	Medial Thrust	p
Vastus Lateralis	42.41 (10.51)	**41.41 (10.01)**	0.013	41.04 (11.17)	0.444	42.93 (13.30)	0.731
Rectus Femoris	37.95 (9.44)	39.01 (19.66)	0.664	42.26 (22.07)	0.178	39.36 (17.23)	0.610
Vastus Medialis	34.90 (8.97)	35.45 (9.44)	0.941	34.37 (10.91)	0.197	35.89 (11.87)	0.336
Lateral Hamstrings	29.07 (16.91)	**35.35 (15.35)**	0.001	25.49 (13.86)	0.166	**34.59 (18.11)**	0.005
Medial Hamstrings	22.98 (12.52)	**35.89 (12.36)**	0.000	21.78 (11.59)	0.829	**30.94 (14.10)**	0.000
Lateral Gastrocnemius	18.71 (10.81)	**24.73 (12.26)**	0.000	17.45 (11.70)	0.304	**22.84 (13.72)**	0.008
Medial Gastrocnemius	16.67 (11.71)	**21.11 (13.32)**	0.000	14.90 (14.02)	0.259	**19.24 (14.72)**	0.010
CCI med:lat	42.47 (16.42)	**54.14 (19.48)**	0.000	41.10 (18.75)	0.811	**49.85 (19.53)**	0.002

Bold numbers are significant different from baseline; $p < .05$.

Medial Thrust condition was accompanied with kinematic modifications towards more Toe-in gait and Wider Steps. While the adjustments were smaller than during the other conditions and no reduction in inter-knee distance was achieved, the KAM reduction was similar to the other two modifications. However, Medial Thrust was also accompanied with increased activation of the flexor muscles by 24% and increased co-contraction. Moreover, Medial Thrust showed an increased peak KFM, which also may cancel in part the reduction of joint loading as assumed from the decrease of the KAM [9,40,41]. This KFM increase was not found for Toe-in or Wider Steps. Therefore, based on the difficulties in performance and the negative effects on the KFM and muscle activations, Medial Thrust shows the least potential for reducing medial joint loading.

The design of our experiment had the following limitations: only three of several possible gait modifications were investigated. We chose to limit ourselves to just the most feasible gait modifications that have been associated with a reduction of the first peak of the KAM [16].

The gait modifications were taught in a fixed order, but this seems not to have affected the outcomes. During the Toe-in condition, participants increased their step width significantly, while this condition preceded the Wider Step condition, so this is likely a result of the heels turning outwards during Toe-in gait. During the Wider Step condition, the foot progression angles went back to normal, thus showing no retention effect of the previous condition. Furthermore, similar muscle activations were found between the Toe-in and Medial Thrust conditions, while muscle activations during Wider Steps clearly deviated, confirming the absence of impact of the order of the trials on kinematics and muscle activations.

Pain is an important symptom in the diagnosis of knee osteoarthritis. Pain can e.g. be caused by the increased load on thinned cartilage in the knee, or by exciting myofascial trigger points, that also increase EMG activity [42], and are often present in combination with knee osteoarthritis [43]. However, our participants did not report significant differences in pain level between the conditions.

Of the 30 people included most ($n = 19$) had KL score 1 or 2. Thus, generalization of the results to more severe KOA is not warranted, as the severity of pain and deteriorated proprioception may influence the muscle activation patterns [44]. However, since gait retraining is meant to prevent KOA progression, our sample fits the targeted patient population.

Many statistical tests were used for testing the changes as a result of the three gait modifications. While this could lead to false positives, the low p-values found in this study point towards real, significant changes. Furthermore, since this study was not the primary aim of the research, no specific power calculation was performed for this secondary study. A lack of power would lead to a low statistical power to detect a difference between conditions. Nevertheless, our study showed convincing results that the gait modifications clearly impact the level of co-contraction around the knee joint differently. Therefore, this study provides a strong argument to further investigate the impact of these co-contractions on the net joint loading, since it could be an important factor in personalizing gait modification strategies.

We investigated only the immediate effect of the performance of novel gait modifications on muscle activations. Novelty of the gait patterns may have influenced outcomes of the gait retraining. From 40 participants, only in 30 participants one or more gait modifications led to more than 10 steps with KAM reduction over 10%. The data presented in this study result from a single first time training session. Patients walked for three minutes per modification, which may not have been sufficient for the gait patterns to be executed naturally [45], without novelty co-contraction. After the training session, participants indicated that the learned gait patterns still felt unnatural, so this might have affected their motor control, i.e. the muscle activation level. Increased co-contraction is often seen during the learning phase [26]. The most efficient coordination strategy will only be used as soon as the new movement is fully acquired [26,46,47]. This suggests that the elevated muscle activations may regress to baseline levels after a longer training period [48].

Nevertheless, it is unknown whether the increased co-contraction led to increases of medial joint loading. Modeling studies showed that muscles contractions substantially contribute to knee joint loading [6,49]. It is estimated that muscle forces may add up to 3.5 times the bodyweight to the knee joint loading during gait, while total peak knee joint loading was estimated to be 4.4 times bodyweight [49]. Quantification of the net knee joint loading from the interplay of present co-contraction and the reduced external KAM cannot be concluded from EMG signals alone, but would require musculoskeletal modeling. Conventional approaches use cost functions that minimize the total muscle activations, thereby neglecting individual muscle activation patterns or co-contractions [50,51]. This limitation also applies to the modeling study of Shull et al. [23], which may explain why in this study inconsistent changes on a group-level in estimated muscle forces for Toe-in gait where found. This calls for future studies with models that include EMG supported estimation of muscle forces [52], to inform decisions on the optimal gait modification for each individual, i.e. providing individualized treatment. For instance, EMG-driven and/or EMG-assisted modeling might contribute to better understanding [53–55]. This study is an incentive to further improve modeling techniques that account for motor control in estimating knee joint loading.

5. Conclusion

Patients with KOA are able to reduce KAM by adopting Wider Steps, without an increase of muscle activations or co-contraction. Reducing KAM by adopting Medial Thrust gait showed increased muscle activations, co-contraction and KFM, thereby comprising the intended decrease in knee load. Applying Toe-in gait showed the greatest KAM reduction, but muscle activations and co-contraction increased dramatically. Since these effects appeared directly following modification, a longer period of training and habituation to the modified gait pattern (particularly Toe-in gait), might reduce such levels of increased co-contraction. Therefore, we recommend that future studies include follow-ups for a longer period of time after gait retraining.

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Declaration of competing interest

There are no conflicts of interest to report.

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