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Determining the optimal gait modification strategy for patients with knee osteoarthritis: Trunk lean or medial thrust?

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ABSTRACT

Background: The gait modification strategies Trunk Lean and Medial Thrust have been shown to reduce the external knee adduction moment (EKAM) in patients with knee osteoarthritis which could contribute to reduced progression of the disease. Which strategy is most optimal differs between individuals, but the underlying mechanism that causes this remains unknown.
Research question: Which gait parameters determine the optimal gait modification strategy for individual patients with knee osteoarthritis?
Methods: Forty-seven participants with symptomatic medial knee osteoarthritis underwent 3-dimensional motion analysis during comfortable gait and with two gait modification strategies: Medial Thrust and Trunk Lean. Kinematic and kinetic variables were calculated. Participants were then categorized into one of the two subgroups, based on the modification strategy that reduced the EKAM the most for them. Multiple logistic regression analysis with backward elimination was used to investigate the predictive nature of dynamic parameters obtained during comfortable walking on the optimal modification gait strategy.
Results: For 68.1 % of the participants, Trunk Lean was the optimal strategy in reducing the EKAM. Baseline characteristics, kinematics and kinetics did not differ significantly between subgroups during comfortable walking. Changes to frontal trunk and tibia angles correlated significantly with EKAM reduction during the Trunk Lean and Medial Thrust strategies, respectively. Regression analysis showed that MT is likely optimal when the frontal tibia angle range of motion and peak knee flexion angle in early stance during comfortable walking are high ($R^2_{Nagelkerke} = 0.12$).
Significance: Our regression model based solely on kinematic parameters from comfortable walking contained characteristics of the frontal tibia angle and knee flexion angle. As the model explains only 12.3 % of variance, clinical application does not seem feasible. Direct assessment of kinetics seems to be the most optimal strategy for selecting the most optimal gait modification strategy for individual patients with knee osteoarthritis.

1. Introduction

Increased knee joint loading during gait appears to be a contributor to the progression of medial tibio-femoral knee osteoarthritis (KOA) [1–4]. Both the external knee adduction moment (EKAM), interpreted as an indirect surrogate measure for medial contact force [5,6], and the external knee flexion moment (EKFM) seem of critical importance in assessing changes in loading during gait [6–8] and risk of KOA progression [7,9–11].

Gait modification strategies that aim to alter trunk motion, knee angles, toe out angle, gait speed or combinations of these parameters have been found to effectively reduce these moments [12–18]. In recent years, biofeedback approaches were tested to reduce the EKAM whereby direct feedback on the EKAM [19,20] or joint contact forces [21] was provided to the patients on a screen in front of them. Although these approaches can be effective, inputs from a clinician on potentially effective modification strategies might still be necessary [21]. The optimal strategy, however, differs per person [12] and the requirements

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to apply such strategies in clinical practice are often not met since complex motion analysis with force measurement is needed to provide adequate feedback. Clinically feasible gait modification strategies that are tailored to the individual are therefore valuable. The Trunk Lean and Medial Thrust strategies seem most successful in reducing the EKAM [12–14,22]. Trunk Lean reduces the lever arm of the ground reaction force about the knee, reduces the distance between the center of pressure and the knee joint center and medially shifts the knee joint center [23]. Medial Thrust reduces the EKAM by medialising the knee during the early stance phase [22,24], which is in line with the observation that the knee adduction angle explains 58 % of peak EKAM variance [25]. The underlying mechanism that explains which of these two strategies is optimal for a specific patient is not well understood. To successfully apply gait modification strategies in clinical practice, there is a need to establish per individual the most effective strategy [12,14]. In order to better understand the underlying mechanism of effective strategy, we aim to (1) find distinctions in achieved alterations between the subgroups based on gait parameters during Medial Thrust and Trunk Lean strategies and (2) to establish which comfortable gait parameters may predict the strategy that reduces the peak EKAM the most for individual persons with knee OA.

2. Methods

2.1. Subjects

Participants (≥50 years) were physician-diagnosed with symptomatic medial tibio-femoral KOA by fulfillment of the ACR-criteria (American College of Rheumatology) [26] and radiographically diagnosed, and participated in response to a locally published news article. Those who were unable to walk without gait aids, experienced impaired gait due to additional orthopedic or neurological deficiencies, or severe impairment to vision or cognition were excluded. Use of pain medication was not controlled for.

The medical ethical committee of the Máxima Medical Center Veldhoven provided ethical approval of the study protocol. Prior to the experiment, all patients signed the informed consent after receiving information about the study.

2.2. Equipment

Kinematics of the most affected leg and the torso were captured by a wireless active 3D-system (Charnwood Dynamics Ltd., Codamotion CX 1, sampling at 200 Hz). A force plate (Advanced Mechanical Technology, Inc., OR 6–7, sampling frequency: 1000 Hz) halfway a 13 m long walkway measured ground reaction forces for one step per trial.

2.3. Segments and axes

After being tracked by 20 infrared markers (Fig. 1), kinematics of the foot, lower and upper leg, pelvis and torso were determined and modeled as rigid bodies in Visual3D (C-motion, Inc., Germantown, MD). The hip joint center was defined using the model by Davis, Ounpuu, Tyburski and JR. [4], the midpoint between the femoral epicondyles and malleoli determined the joint centers of the knee and ankle, respectively. Ankle, knee and hip rotations were calculated in a local coordinate system with the origin at the joint centers, relative to the distal segment.

2.4. Experimental protocol

After marker placement, participants familiarized to the environment by walking comfortably for at least 5 min. A static standing trial of 8 s was captured. Then, participants implemented the conditions comfortable walking, Trunk Lean and Medial Thrust. Participants were asked to implement TL and MT to the greatest possible extent within their self-determined comfortable boundaries and were instructed by a visual example and verbally:

- Comfortable walking: *"Walk freely and comfortably as you would on the street"*.
- Trunk Lean: "At heel strike, lean sideways with the torso towards the foot on the most affected leg and return back slowly during stances".
- Medial Thrust: "Move the most affected knee inwards during stance".

Participants walked barefoot and always started with comfortable walking. The modification strategies were carried out in random order using a coin toss. After a 3 min period of comfortable walking before each condition, participants practiced at least 5 and maximally 15 min per condition until they felt comfortable to implement the instructions in their gait. Six successful trials were captured per condition. None of the patients used the optional resting period between conditions.

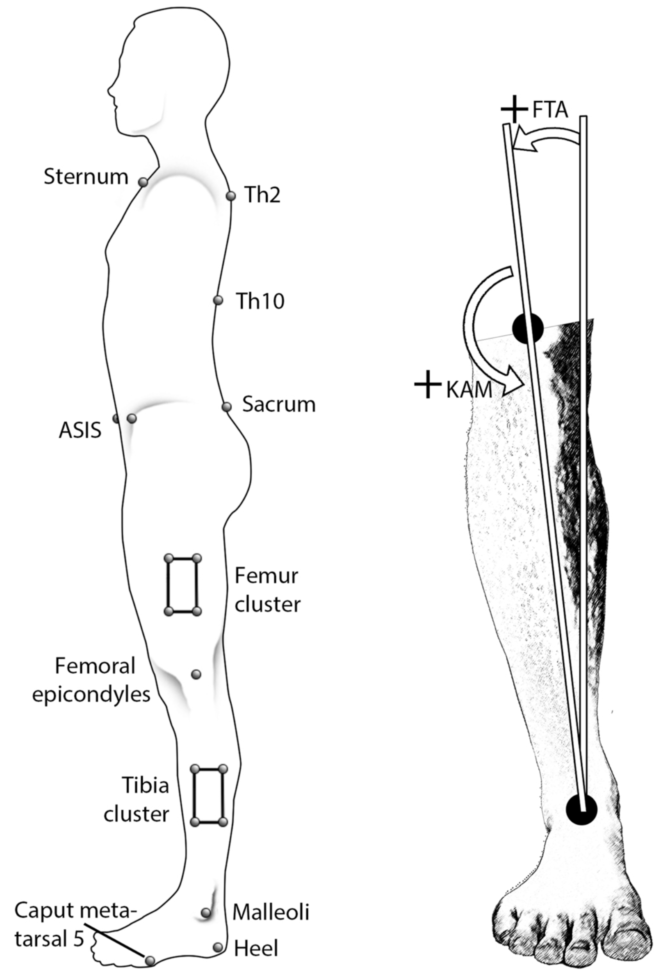

Fig. 1. Marker placement for the modeling of trunk, pelvis, upper leg, lower leg, lower leg and foot segments, and definitions of positive external knee adduction moments and frontal tibia angles.

2.5. Data analysis

Data was recorded with Codamotion Analysis (Charnwood Dynamics Ltd.) and analyzed in Visual3D (C-Motion Inc.). After interpolation with a third order polynomial, force plate data and marker positions were filtered with a Butterworth filter with a cut-off frequency of 6 Hz and 20 Hz, respectively. The stance phase was determined by a threshold of 20 N on the vertical ground reaction force. Joint moments were calculated through 6 degree of freedom inverse dynamics. All timelines were normalized to 100 % of stance phase.

Peak moments of the first and last 50 % of the stance phase defined early and late stance EKAM and EKFM. The impulse of these moments were calculated as the time integral during stance.

To assess the modification amplitudes of TL and MT, positive frontal trunk angles were defined relative to the lab in the direction of the most affected leg. Positive frontal plane tibia angles occurred when the knee was medial to the ankle. The peak knee flexion angle during early stance was defined as the peak flexion angle during the first 30 % of the stance phase. The mean speed of the sacral marker was calculated in the direction of walking during the stance phase to represent gait speed. Outcomes were determined for six trials after which the means were calculated for each participant.

2.6. Statistical analysis

Statistical analyses were conducted in SPSS for Windows (version 27). All kinematics and kinetics were checked for normality (skewness $-1 \geq 1$) and mean and SD were calculated for each condition when normally distributed.

Participants were categorized into the TL subgroup or MT subgroup based on which strategy reduced the overall peak EKAM the most. A similar categorization was conducted based on the EKAM impulse reduction. Independent t-tests were used to compare subgroups for baseline characteristics, dynamic characteristics during each condition and to compare changes during MT and TL relative to comfortable walking. A paired t-test was used for comparisons between conditions. A Bonferroni correction was applied to control for the family-wise error rate, with a significance level set at $p < 0.05$.

Pearson correlations were used to test if changes to the peak tibia and trunk angles were associated with EKAM changes and to establish the correlation between the peak frontal tibia and trunk angle during comfortable walking and their change during Medial Thrust and Trunk lean, respectively.

To test predictors, multiple logistic regression analysis with backward elimination (elimination criterion: $p > 0.20$) was used to assess which of the following parameters obtained during comfortable walking contributed to the formation of the two subgroups: overall peak EKAM, early and late stance peak EKAM, EKAM impulse, early stance peak knee flexion angle, peak frontal trunk angle and tibia range of motion, frontal trunk and tibia angle at the moment of peak EKAM and gait speed. Goodness of fit of the model was evaluated using Nagelkerke R^2 [27].

3. Results

Forty-seven symptomatic patients with knee osteoarthritis were included in the study (Table 1). Twenty-nine participants were included from our previous study [12] and eighteen were added for this study. All conditions were completed without difficulties. All kinematics and kinetics were normally distributed. KOOS scores displayed a wide range for pain (overall: 22–86, TL subgroup: 31–86, MT subgroup: 22–75) and function (overall: 35–93, TL subgroup: 38–93, MT subgroup: 35–81), and were not significantly different between subgroups. When subgroups were created based on peak EKAM reduction, TL was most effective for 68.1 % of the participants ($n = 32$) and MT was most effective for 31.9 % ($n = 15$). Between the TL and MT subgroups, no significant differences were found for baseline characteristics (Table 1).

Table 1
Baseline patient characte` on peak EKAM reduction.

	Overall	Subgroups		Subgroup comparison
Baseline characteristics	**n = 47** *mean (SD)*	**TL (n = 32)** *mean (SD)*	**MT (n = 15)** *mean (SD)*	***p***
Height (m)	1.71 (0.10)	1.72 (0.10)	1.71 (0.09)	0.81
Weight (kg)	76.8 (11.7)	77.4 (13.0)	75.6 (9.1)	0.64
Age (years)	61.8 (6.5)	61.6 (6.7)	62.4 (6.7)	0.69
BMI (kg/m^2)	26.2 (3.2)	26.2 (3.3)	26.1 (3.2)	0.52
KOOS pain	58.0 (16.7)	59.4 (17.7)	55.0 (15.0)	0.40
KOOS function	63.2 (17.1)	64.3 (18.7)	60.9 (14.2)	0.53
Knee add. angle (deg)	3.5 (3.2)	3.2 (4.9)	4.1 (2.3)	0.50
Females (n (%))	27 (57.4%)	18 (56.3%)	7 (46.7%)	-

Impulse-based subgroup data is presented in Appendix 1.

Overall, Trunk Lean reduced the peak EKAM more than Medial Thrust (0.08 Nm•BwHt^{-1}, $p = 0.004$). There was no significant difference between TL and MT in their effect on EKAM impulse (0.002 Nms•BwHt^{-1}, $p = 0.61$). Paired t-test outcomes show that frontal trunk angles were significantly increased in both subgroups during TL. Frontal tibia angles were increased for both subgroups during MT, but after correction for multiple testing this was only significant for the MT subgroup. Changes to peak frontal trunk angles during TL correlated significantly with peak EKAM reductions ($r = 0.42$, $p = 0.003$) and impulse ($r = 0.53$, $p < 0.001$). Similarly during MT, changes to peak frontal tibia angles correlated significantly with peak EKAM reductions ($r = 0.86$, $p < 0.001$) and impulse ($r = 0.47$, $p = 0.001$). Significant correlations were found between the peak frontal tibia angle during comfortable walking and its change during Medial Thrust ($r = 0.59$, $p = <0.001$) and between the peak frontal trunk angle during comfortable walking and its change during Trunk Lean ($r = -0.32$, $p = 0.03$).

In Fig. 2 and Table 2, kinematics and kinetics during comfortable walking are presented. No significant differences were found between the TL and MT subgroups.

A comparison of gait characteristics between these subgroups during TL and MT is presented in Table 3. Overall and early stance peak EKAM were significantly reduced relative to comfortable walking in all cases. The timing of the peak EKAM occurred significantly later in the stance phase for the MT subgroup during MT. This change was also significant between subgroups. Late stance peak EKAM was only reduced significantly during TL. Trunk and tibia angles changes were significant and in accordance with the instructions in both subgroups, except for the frontal tibia angle during MT in the TL subgroup. Trunk angle changes were on average more than 6 times greater during TL relative to MT. Gait speed was significantly reduced in all conditions relative to comfortable walking but these changes were not significantly different between subgroups.

Regression analysis resulted in a model that predicts the optimal subgroup based on two parameters obtained from the comfortable walking condition (Table 4) containing the early stance range of motion of the frontal tibia angle and the peak knee flexion angle ($R^2_{Nagelkerke} = 0.12$) as significant predictors. The larger these parameters are, the more likely it is that MT is the optimal strategy.

Subgroup analyses based on EKAM impulse were conducted as well (see Appendix 2–5). The main differences with peak EKAM analyses were attributable to a significantly reduced gait speed which affects the EKAM impulse directly, but the analyses led to similar outcomes.

4. Discussion

We aimed to understand why the optimal strategy differs between individuals after imposing two gait modification strategies by comparing the effects on relevant gait parameters between subgroups (based on strategy with the largest effect). In addition, we aimed to evaluate whether comfortable gait characteristics at baseline can predict the optimal strategy for an individual patient. The emergence of

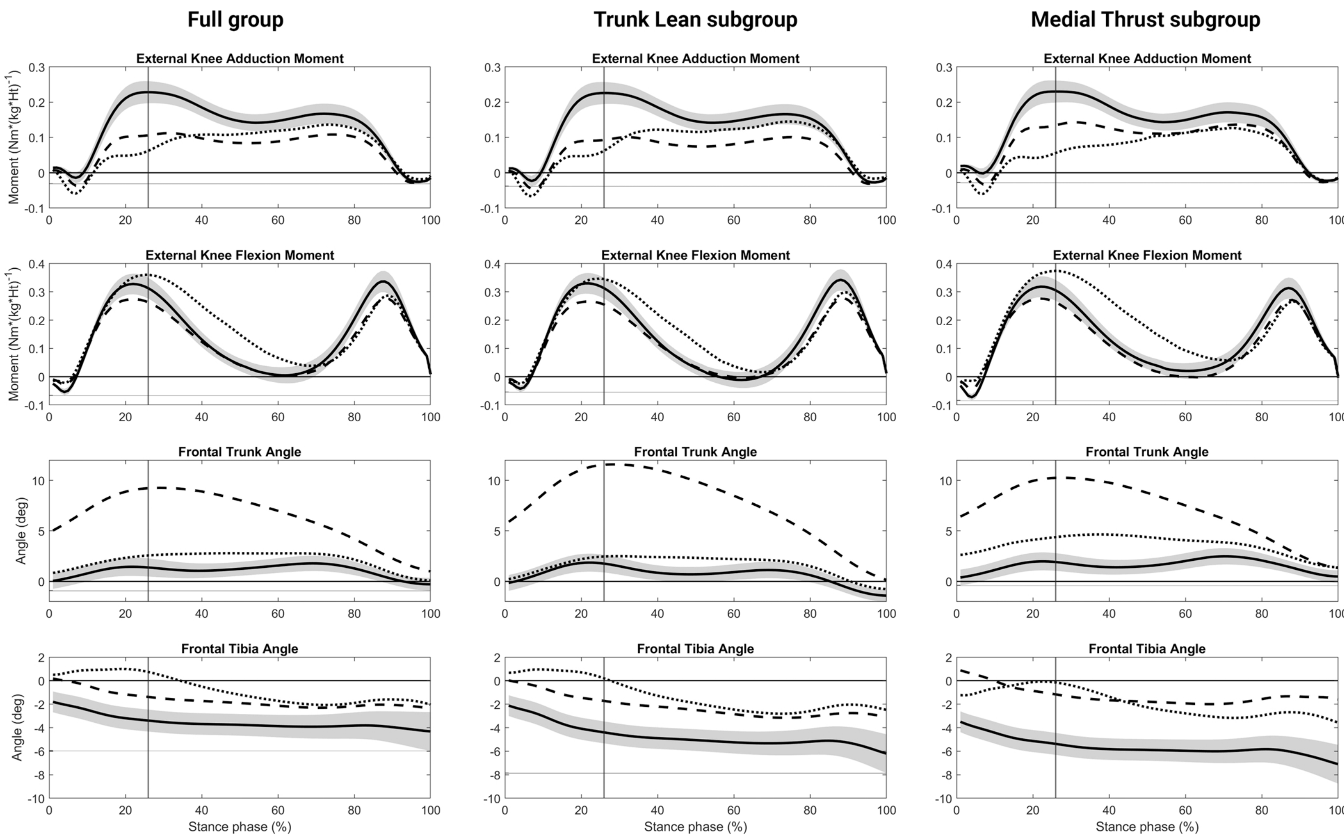

Fig. 2. Timelines of the knee adduction and flexion moments and the frontal trunk and tibia angles during the stance phase for the full group and per subgroup. Comfortable Walking (solid, including 95 % CI in gray), Medial Thrust (dotted) and Trunk Lean (dashed) are presented. A vertical line is drawn where the peak EKAM occurs.

subgroups seems highly related to the magnitude by which the tibia range of motion is modified during MT in one third of patients. Regression analysis suggests that two kinematic parameters from comfortable walking can be used in a model to predict the strategy that reduces the EKAM the most. The MT strategy is likely most optimal when the early stance ROM of the frontal tibia angle and the maximal knee flexion angle are large.

As expected [12,16,28], the tibia and trunk angles were modified in accordance with the instructions, and were significantly correlated with EKAM reductions. The modification amplitude seems related to the amplitude at baseline, as the peak tibia and trunk angles during comfortable walking were significantly correlated to their change during MT and TL, respectively. As no significant changes to peak EKFM were found, we expect that the interventions predominantly reduced the frontal knee moment arm and that a potential transfer of moments from frontal to sagittal plane was minimal. Similar to our previous study [12], the Trunk Lean strategy reduced the EKAM the most for about two-thirds of the patients. Although the trunk angle modification during the TL condition did not differ significantly between the subgroups, the peak EKAM was reduced more in the TL subgroup. A similar effect was found during the MT condition, where the EKAM was reduced the most in the MT group while the tibia angle modification in both groups did not significantly differ between groups. However, during MT, the trunk angle was modified in both subgroups as well, which could also have resulted in a peak EKAM reduction. It seems therefore reasonable to further investigate the extent to which both strategies could be complementary.

Whereas the change in peak tibia angle did not differ significantly, the change in tibia angle at the peak EKAM in the MT subgroup was larger relative to the TL subgroup by a factor > 3. Therefore, the mechanism by which Medial Thrust emerges as the most effective strategy in one third of the group seems largely related to the timing of the tibia angle modification during MT. The difference in timing of the peak EKAM became significant between subgroups during both TL and MT. This outcome could potentially be a valuable predictor although the interpretation is complex. The first peak EKAM was diminished in the MT subgroup during MT, and so the typical M-shaped curve is no longer present for this subgroup. Thus, comparisons between groups based on the location of early stance peak values becomes of questionable value. Our results also show that both subgroups significantly modified their trunk angle at the peak EKAM during the TL condition. However, the MT subgroup modified the tibia angle at the peak EKAM over 3 times more than the TL subgroup when performing the MT strategy. This could imply that performing MT effectively is more challenging than TL for most people, but that those who synchronize their tibia modification to the peak EKAM reduce the knee moment more than what they can achieve with the TL strategy. Lower extremity alignment, muscle strength and coordination might all play a role in explaining why the performance of these strategies differs between participants. From our data, we were able to show that participants differ in their performance, but unable to determine why. Future studies should investigate the potential of training patients to not only impose a modification magnitude but to also optimize the timing thereof.

Regression analysis supports the idea that the frontal tibia angle during comfortable walking is an important parameter, as in assessing the optimal modification strategy from comfortable walking the frontal tibia range of motion contributes significantly to the predictive model. We hypothesize that for individuals with a higher peak frontal tibia angle (knee projects lateral to the ankle) during comfortable walking the frontal knee moment arm is more effectively reduced by MT relative to TL.

As the regression model explained only 12.3 % of variance, the use of

Table 2
Comparison of dynamic gait characteristics during comfortable walking.

n = 47 Characteristics during comfortable walking	Overall TL (n = 32) *mean (SD)*	Subgroups MT (n = 15) *mean (SD)*	 *p*	Subgroup comparison *mean (SD)*
Peak EKAM (Nm•BwHt^{-1})	0.23 (0.11)	0.24 (0.11)	0.22 (0.10)	0.70
EKAM impulse (Nms•BwHt^{-1})	0.10 (0.07)	0.10 (0.07)	0.10 (0.07)	0.87
E.S. EKAMp (Nm•BwHt^{-1})	0.23 (0.11)	0.23 (0.12)	0.22 (0.11)	0.72
L.S. EKAMp (Nm•BwHt^{-1})	0.17 (0.10)	0.18 (0.11)	0.17 (0.09)	0.83
EKAMp timing (%stance)	26.0 (7.88)	27.6 (7.2)	22.8 (8.6)	0.05
E.S. EKFMp (Nm•BwHt^{-1})	0.33 (0.02)	0.34 (0.16)	0.32 (0.14)	0.84
Peak trunk angle (deg)	2.7 (2.1)	2.7 (2.1)	2.8 (2.3)	0.83
Trunk angle at EKAMp (deg)	1.7 (2.5)	1.5 (2.5)	2.2 (2.6)	0.44
Peak tibia angle (deg)	0.9 (4.7)	0.7 (4.8)	1.3 (4.7)	0.73
E.S. tibia angle ROM (deg)	3.13 (1.0)	3.2 (1.1)	3.0 (0.7)	0.44
Tibia angle at EKAMp (deg)	-1.7 (4.9)	-1.4 (5.3)	-2.3 (4.0)	0.58
E.S. peak knee flexion (deg)	17.1 (7.0)	18.3 (6.2)	15.0 (8.2)	0.18
Gait speed (m/s)	1.19 (0.11)	1.20 (0.10)	1.20 (0.14)	0.49

EKAMp = peak EKAM, EKFMp = peak external knee flexion moment, E.S. = early stance, L.S. = late stance, angles are all determined in the frontal plane. Impulse-based subgroup data is presented in Appendix 2.

this model in clinical practice to predict the optimal gait modification strategy does not seem feasible. Therefore, kinetic data seems to be required, causing relatively scarcely available high-end equipment to be required to assess the EKAM directly. Future studies should explore the criteria on which clinical decisions for choice of gait modification strategy can be based in the absence of kinetic data. For instance, as both strategies effectively reduced the EKAM in all patients, the preferred strategy by the patient and adherence to training might ultimately determine the modification strategy that should be implemented.

The study considered two modification strategies as earlier research showed that MT and TL can reduce the EKAM very effectively [12,22], and are based on different biomechanical mechanisms that are not mutually exclusive. Other approaches, such as combining strategies through biofeedback systems to minimize the EKAM on an individual level [15,19,21,29,30] can be effective as well, but require continuous use of high-end measurement tools. In addition, as characteristics of the resulting modification strategies cannot be predicted on an individual level, potential detrimental effects in the kinematic chain should be carefully assessed. This currently relies on a combination of technologies that are not applicable or available in most clinical settings. Use of such high-end technologies in a laboratory environment to determine the optimal gait modification strategy prior to clinical training might currently be the most feasible approach.

Long term effects of individually selected gait modification strategies are still unclear, should be carried out with care to prevent potential harmful redistribution of loads [31] and should thus be tested before applied systematically in clinical practice. It should be noted that although the EKAM was shown to be related to OA progression [7,9–11], it is an indirect measure for contact force [5,6] and may in some parts of the stance phase be insufficiently predictive of contact force [32]. Recent studies showed that early and late stance peak contact force are nonetheless correlated well with the EKAM [33] and EKFM [34]. As the relation between OA progression mechanisms and biomechanical parameters are not fully understood, clinical application of gait modification strategies and methods for evaluation should be considered with care.

All patients received enough time to adapt to the strategy so that it could be performed comfortably, but gait speed was reduced relative to comfortable walking and likely influenced gait characteristics such as the peak EKAM [35]. Future studies should therefore address the extent to which gait speed can be retained through training while assessing the EKAM.

As our regression analysis was underpowered for more extensive multivariate regression analyses, future studies should aim to use a larger dataset in order to investigate stronger predictive models without any need of kinetic parameters.

Although the Trunk Lean strategy reduced the EKAM the most overall, it was the optimal strategy for only 68.1% of the participants, highlighting the need for an individual approach when selecting modification strategies. Our analyses suggest that the frontal tibia angle during comfortable walking and its modification (or lack thereof) during TL and MT is relevant in predicting which strategy reduces the EKAM the most. However, although less feasible for clinical practice, direct assessment of kinetics to determine the optimal strategy remains most effective.

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CRediT authorship contribution statement

All authors contributed to the design, interpretation of data and statistical outcomes, revisions and approval before submission. Collection and assembly of data was conducted by the first author.

Declaration of Competing Interest

All authors declare no potential conflicts of interest concerning authorship and publication of this article.

Appendix A. Baseline patient characteristics overall and per subgroup based on EKAM impulse reduction

		Subgroup defining parameter					
	Overall	EKAM peak reduction			EKAM Impulse reduction		
Baseline characteristics	**n = 47**	**TL (n = 32)**	**MT (n = 15)**	***p***	**TL (n = 32)**	**MT (n = 15)**	***p***
mean (SD)	*mean (SD)*	*mean (SD)*	*ΔTL-MT*	*mean (SD)*	*mean (SD)*	*ΔTL-MT*	
Height (m)	1.71 (0.10)	1.72 (0.10)	1.71 (0.09)	0.81	1.72 (0.11)	1.70 (0.08)	0.14
Weight (kg)	76.8 (11.7)	77.4 (13.0)	75.6 (9.1)	0.64	77.6 (12.9)	75.94 (10.9)	0.45
Age (years)	61.8 (6.5)	61.6 (6.7)	62.4 (6.7)	0.69	62.0 (6.7)	61.7 (6.6)	0.69

(*continued on next page*)

Table 3
Comparison of gait characteristics between MT and TL.

Condition	Absolute outcomes			Modifications to comfortable gait		
	TL (n = 32) *mean (SD)*	MT (n = 15) *mean (SD)*	*p*	TL (n = 32) *mean (SD)*	MT (n = 15) *mean (SD)*	*p*
Medial Thrust						
Peak EKAM (Nm•BwHt^{-1})	0.20 (0.11)	0.14 (0.07)	0.04	**-0.03 (0.04)***	**-0.08 (0.05)***	0.004
EKAM impulse (Nm•BwHt^{-1})	0.07 (0.05)	0.05 (0.04)	0.10	-0.04 (0.15)	-0.04 (0.07)	0.03
E.S. EKAMp (Nm•BwHt^{-1})	0.17 (0.10)	0.11 (0.07)	0.02	**-0.06 (0.07)***	**-0.11 (0.07)***	0.02
L.S. EKAMp (Nm•BwHt^{-1})	0.17 (0.11)	0.13 (0.07)	0.17	-0.01 (0.05)	**-0.04 (0.04)***	0.01
EKAMp timing (%stance)	29.1 (14.6)	40.9 (10.8)	0.01	1.6 (17.6)	**18.1 (12.9)***	**0.002***
E.S. EKFMp (Nm•BwHt^{-1})	0.39 (0.30)	0.38 (0.18)	0.90	0.06 (0.22)	0.06 (0.12)	0.94
Peak trunk angle (deg)	3.9 (3.3)	5.6 (5.1)	0.18	**1.2 (2.1)***	2.8 (4.0)	0.09
Trunk angle at EKAMp (deg)	2.2 (4.5)	4.2 (4.8)	0.18	0.7 (3.2)	2.0 (3.5)	0.19
Peak tibia angle (deg)	2.8 (3.9)	5.2 (3.9)	0.06	2.1 (4.3)	**3.9 (3.4)***	0.15
E.S. tibia angle ROM (deg)	1.6 (3.7)	1.8 (4.0)	0.85	1.7 (3.9)	1.3 (4.4)	0.73
Tibia angle at EKAMp (deg)	0.0 (3.7)	2.2 (3.2)	0.047	1.4 (5.0)	**4.5 (4.6)***	0.047
Peak E.S. knee flexion (deg)	26.2 (9.3)	24.8 (17.0)	0.71	**7.8 (7.9)***	**10.3 (10.3)***	0.38
Gait speed (m/s)	1.03 (0.18)	0.93 (0.20)	0.10	**-0.17 (0.15)***	**-0.24 (0.15)***	0.12
Trunk Lean						
Peak EKAM (Nm•BwHt^{-1})	0.15 (0.11)	0.17 (0.08)	0.45	**-0.09 (0.05)***	**-0.05 (0.04)***	0.01
EKAM impulse (Nm•BwHt^{-1})	0.06 (0.06)	0.07 (0.06)	0.71	-0.04 (0.03)	-0.03 (0.02)	0.19
E.S. EKAMp (Nm•BwHt^{-1})	0.14 (0.11)	0.16 (0.08)	0.57	**-0.10 (0.05)***	**-0.06 (0.05)***	0.06
L.S. EKAMp (Nm•BwHt^{-1})	0.12 (0.11)	0.14 (0.09)	0.69	**-0.05 (0.05)***	**-0.03 (0.03)***	0.17
EKAMp timing (%stance)	24.6 (12.2)	33.6 (12.4)	0.02	-3.0 (14.3)	10.8 (12.2)	0.002*
E.S. EKFMp (Nm•BwHt^{-1})	0.32 (0.18)	0.28 (0.15)	0.58	-0.02 (0.10)	-0.03 (0.12)	0.68
Peak trunk angle (deg)	13.8 (6.7)	10.6 (9.2)	0.19	**11.1 (5.9)***	**7.8 (7.8)***	0.12
Trunk angle at EKAMp (deg)	11.3 (8.5)	9.6 (9.7)	0.53	**9.8 (7.4)***	**7.4 (8.2)***	0.33
Peak tibia angle (deg)	1.2 (3.9)	2.9 (3.2)	0.16	0.5 (2.7)	1.6 (3.0)	0.20
E.S. tibia angle ROM (deg)	2.1 (3.7)	1.6 (3.9)	0.71	1.2 (3.8)	1.5 (3.7)	0.85
Tibia angle at EKAMp (deg)	-1.2 (3.8)	2.9 (3.2)	0.84	0.2 (3.1)	0.8 (2.8)	0.50
Peak E.S. knee flexion (deg)	20.0 (8.6)	16.5 (10.5)	0.23	1.6 (5.5)	1.9 (5.4)	0.85
Gait speed (m/s)	1.06 (0.15)	1.03 (0.15)	0.60	**-0.14 (0.11)***	**-0.14 (0.14)***	0.99

EKAMp = peak EKAM, EKFMp = peak external knee flexion moment, E.S. = early stance, L.S. = late stance, angles are all determined in the frontal plane, *) significant difference (after Bonferroni correction: $p \leq 0.00038$) relative to comfortable walking as determined by a paired t-test. Impulse-based subgroup data is presented in Appendix 3 and 4.

Table 4
Parameters from comfortable walking that predict the optimal subgroup.

Model parameters	OR	95% CI	*p*	Nagelkerke R^2
Early stance frontal tibia angle ROM	0.61	0.30 – 1.25	0.18	0.12
Early stance peak knee flexion angle	0.90	0.80 – 1.02	0.09	

Impulse-based subgroup data is presented in Appendix 5.

(*continued*)

	Overall	Subgroup defining parameter					
		EKAM peak reduction			EKAM Impulse reduction		
BMI (kg/m^2)	26.2 (3.2)	26.2 (3.3)	26.1 (3.2)	0.52	26.2 (3.1)	26.1 (3.4)	0.66
KOOS pain	58.0 (16.7)	59.4 (17.7)	55.0 (15.0)	0.40	59.1 (18.6)	56.8 (15.2)	0.38
KOOS function	63.2 (17.1)	64.3 (18.7)	60.9 (14.2)	0.53	61.8 (18.3)	64.6 (16.5)	0.27
Knee add. angle (deg)	3.5 (3.2)	3.2 (4.9)	4.1 (2.3)	0.50	3.9 (3.6)	2.6 (5.6)	0.13
Females (n (%))	27 (57.4%)	18 (56.3%)	7 (46.7%)		20 (62.5)	9 (60.0%)	

Appendix B. Comparison of dynamic gait characteristics during comfortable walking (Table 2 addendum)

	Overall	Subgroup defining parameter					
		EKAM peak reduction			EKAM Impulse reduction		
Characteristics during comfortable walking *mean (SD)*	**n = 47** *mean (SD)*	**TL (n = 32)** *mean (SD)*	**MT (n = 15)**	***p*** *mean (SD)*	**TL (n = 32)** *mean (SD)*	**MT (n = 15)**	***p***
Peak EKAM (Nm•BwHt^{-1})	0.23 (0.11)	0.24 (0.11)	0.22 (0.10)	0.70	0.25 (0.10)	0.20 (0.12)	0.22
EKAM impulse (Nms•BwHt^{-1})	0.10 (0.07)	0.10 (0.07)	0.10 (0.07)	0.87	0.11 (0.06)	0.09 (0.07)	0.36
E.S. EKAMp (Nm•BwHt^{-1})	0.23 (0.11)	0.23 (0.12)	0.22 (0.11)	0.72	0.23 (0.10)	0.20 (0.13)	0.18
L.S. EKAMp (Nm•BwHt^{-1})	0.17 (0.10)	0.18 (0.11)	0.17 (0.09)	0.83	0.18 (0.10)	0.16 (0.11)	0.50

(*continued on next page*)

(*continued*)

	Overall	Subgroup defining parameter: EKAM peak reduction			EKAM Impulse reduction		
EKAMp timing (%stance)	26.0 (7.88)	27.6 (7.2)	22.8 (8.6)	0.05	28.1 (5.2)	21.8 (10.7)	0.01
E.S. EKFMp (Nm•BwHt^{-1})	0.33 (0.02)	0.34 (0.16)	0.32 (0.14)	0.84	0.34 (0.16)	0.31 (0.13)	0.46
Peak trunk angle (deg)	2.7 (2.1)	2.7 (2.1)	2.8 (2.3)	0.83	2.9 (2.1)	2.4 (2.3)	0.48
Trunk angle at EKAMp (deg)	1.7 (2.5)	1.5 (2.5)	2.2 (2.6)	0.44	1.8 (2.5)	1.6 (2.5)	0.78
Peak tibia angle (deg)	0.9 (4.7)	0.7 (4.8)	1.3 (4.7)	0.73	0.6 (4.6)	1.6 (5.0)	0.50
E.S. tibia angle ROM (deg)	3.13 (1.0)	3.2 (1.1)	3.0 (0.7)	0.44	3.3 (1.1)	2.8 (0.8)	0.11
Tibia angle at EKAMp (deg)	-1.7 (4.9)	-1.4 (5.3)	-2.3 (4.0)	0.58	-1.8 (5.0)	-1.6 (4.6)	0.91
E.S. peak knee flexion (deg)	17.1 (7.0)	18.3 (6.2)	15.0 (8.2)	0.18	17.9 (6.1)	15.5 (8.8)	0.27
Gait speed (m/s)	1.19 (0.11)	1.20 (0.10)	1.20 (0.14)	0.49	1.21 (0.10)	1.13 (0.12)	0.02

EKAMp = EKAM peak, EKFMp = peak external knee flexion moment, E.S. = early stance, L.S. = late stance, angles are all determined in the frontal plane.

Appendix C. Comparison of dynamic patient characteristics between subgroups

	Subgroup defining parameter: EKAM peak reduction			EKAM Impulse reduction		
	TL (n = 32) *mean (SD)*	**MT (n = 15)** *mean (SD)*	***p***	**TL (n = 32)** *mean (SD)*	**MT (n = 15)** *mean (SD)*	***p***
Medial Thrust condition						
Peak EKAM (Nm•BwHt^{-1})	0.20 (0.11)	0.14 (0.07)	0.04	0.20 (0.10)	0.14 (0.07)	0.04
EKAM impulse (Nm•BwHt^{-1})	0.07 (0.05)	0.05 (0.04)	0.10	0.08 (0.05)	0.04 (0.04)	0.02
E.S. EKAMp (Nm•BwHt^{-1})	0.17 (0.10)	0.11 (0.07)	0.02	0.17 (0.10)	0.11 (0.07)	0.03
L.S. EKAMp (Nm•BwHt^{-1})	0.17 (0.11)	0.13 (0.07)	0.17	0.18 (0.10)	0.11 (0.08)	0.02
EKAMp timing (%stance)	29.1 (14.6)	40.9 (10.8)	0.01	32.0 (14.3)	34.7 (15.2)	0.55
E.S. EKFMp (Nm•BwHt^{-1})	0.39 (0.30)	0.38 (0.18)	0.90	0.39 (0.29)	0.40 (0.20)	0.89
Peak trunk angle (deg)	3.9 (3.3)	5.6 (5.1)	0.18	3.9 (3.4)	5.6 (5.0)	0.18
Trunk angle at EKAMp (deg)	2.2 (4.5)	4.2 (4.8)	0.18	2.4 (4.6)	3.8 (4.9)	0.33
Peak tibia angle (deg)	2.8 (3.9)	5.2 (3.9)	0.06	2.7 (3.8)	5.3 (4.0)	0.04
E.S. tibia angle ROM (deg)	1.6 (3.7)	1.8 (4.0)	0.85	1.4 (3.6)	2.1 (4.1)	0.57
Tibia angle at EKAMp (deg)	0.0 (3.7)	2.2 (3.2)	0.047	0.0 (3.8)	2.2 (3.1)	0.048
E.S. peak knee flexion (deg)	26.2 (9.3)	24.8 (17.0)	0.71	26.1 (17.4)	25.1 (17.4)	0.79
Gait speed (m/s)	1.03 (0.18)	0.93 (0.20)	0.10	1.03 (0.17)	0.93 (0.22)	0.09
Trunk Lean condition						
Peak EKAM (Nm•BwHt^{-1})	0.15 (0.11)	0.17 (0.08)	0.45	0.16 (0.11)	0.16 (0.09)	0.95
EKAM impulse (Nm•BwHt^{-1})	0.06 (0.06)	0.07 (0.06)	0.71	0.06 (0.06)	0.06 (0.06)	0.83
E.S. EKAMp (Nm•BwHt^{-1})	0.14 (0.11)	0.16 (0.08)	0.57	0.15 (0.10)	0.14 (0.10)	0.79
L.S. EKAMp (Nm•BwHt^{-1})	0.12 (0.11)	0.14 (0.09)	0.69	0.13 (0.11)	0.13 (0.10)	0.96
EKAMp timing (%stance)	24.6 (12.2)	33.6 (12.4)	0.02	25.8 (12.9)	30.9 (12.6)	0.21
E.S. EKFMp (Nm•BwHt^{-1})	0.32 (0.18)	0.28 (0.15)	0.58	0.32 (0.18)	0.29 (0.14)	0.55
Peak trunk angle (deg)	13.8 (6.7)	10.6 (9.2)	0.19	13.6 (6.9)	11.0 (9.1)	0.28
Trunk angle at EKAMp (deg)	11.3 (8.5)	9.6 (9.7)	0.53	11.7 (7.9)	8.9 (10.5)	0.32
Peak tibia angle (deg)	1.2 (3.9)	2.9 (3.2)	0.16	1.3 (3.9)	2.7 (3.2)	0.26
E.S. tibia angle ROM (deg)	2.1 (3.7)	1.6 (3.9)	0.71	2.1 (3.6)	1.5 (4.1)	0.65
Tibia angle at EKAMp (deg)	-1.2 (3.8)	2.9 (3.2)	0.84	-1.5 (3.6)	-0.9 (3.0)	0.56
E.S. peak knee flexion (deg)	20.0 (8.6)	16.5 (10.5)	0.23	19.8 (8.4)	16.9 (10.8)	0.32
Gait speed (m/s)	1.06 (0.15)	1.03 (0.15)	0.60	1.06 (0.15)	1.02 (0.15)	0.32

EKAMp = EKAM peak, EKFMp = peak external knee flexion moment, E.S. = early stance, L.S. = late stance, angles are all determined in the frontal plane.

Appendix D. Changes of dynamic patient characteristics relative to comfortable walking

	Subgroup defining parameter: EKAM peak reduction			EKAM Impulse reduction		
	TL (n = 32) *mean (SD)*	**MT (n = 15)** *mean (SD)*	**p**	**TL (n = 32)** *mean (SD)*	**MT (n = 15)** *mean (SD)*	**p**
Medial Thrust condition						
Peak EKAM (Nm•BwHt^{-1})	**-0.03 (0.04)** *	**-0.08 (0.05)** *	0.004	**-0.04 (0.05)** *	**-0.06 (0.07)** *	0.23
EKAM impulse (Nm•BwHt^{-1})	-0.04 (0.15)	-0.04 (0.07)	0.03	-0.03 (0.14)	**-0.05 (0.08)** *	0.08
E.S. EKAMp (Nm•BwHt^{-1})	**-0.06 (0.07)** *	**-0.11 (0.07)** *	0.02	**-0.07 (0.06)** *	**-0.09 (0.10)** *	0.49
L.S. EKAMp (Nm•BwHt^{-1})	-0.01 (0.05)	**-0.04 (0.04)** *	0.01	0.00 (0.04)	**-0.05 (0.04)** *	**< 0.001**
EKAMp timing (%stance)	1.6 (17.6)	**18.1 (12.9)** *	**0.002** *	3.9 (16.5)	**13.0 (19.6)** *	0.10
E.S. EKFMp (Nm•BwHt^{-1})	0.06 (0.22)	0.06 (0.12)	0.94	0.04 (0.21)	0.09 (0.15)*	0.45
Peak trunk angle (deg)	**1.2 (2.1)** *	2.8 (4.0)	0.09	**1.0 (2.08)** *	**3.2 (3.8)** *	0.02
Trunk angle at EKAMp (deg)	0.7 (3.2)	2.0 (3.5)	0.19	0.6 (3.2)	**2.2 (3.4)** *	0.11
Peak tibia angle (deg)	2.1 (4.3)	**3.9 (3.4)** *	0.15	**2.1 (4.2)** *	**3.7 (3.7)** *	0.21
E.S. tibia angle ROM (deg)	1.7 (3.9)	1.3 (4.4)	0.73	1.8 (3.8)	0.99 (4.5)	0.50
Tibia angle at EKAMp (deg)	1.4 (5.0)	**4.5 (4.6)** *	0.047	1.7 (5.0)	**3.8 (5.1)** *	0.19
E.S. knee flexion peak (deg)	**7.8 (7.9)** *	**10.3 (10.3)** *	0.38	**8.2 (7.6)** *	**9.6 (11.0)** *	0.61
Gait speed (m/s)	**-0.17 (0.15)** *	**-0.24 (0.15)** *	0.12	**-0.18 (0.16)** *	**-0.20 (0.15)** *	0.71

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	Subgroup defining parameter					
	EKAM peak reduction			EKAM Impulse reduction		
	TL (n = 32) *mean (SD)*	**MT (n = 15)** *mean (SD)*	**p**	**TL (n = 32)** *mean (SD)*	**MT (n = 15)** *mean (SD)*	**p**
Trunk Lean condition						
Peak EKAM (Nm•BwHt^{-1})	**-0.09 (0.05)***	**-0.05 (0.04)***	0.01	**-0.09 (0.04) ***	**-0.05 (0.04)***	**0.004**
EKAM impulse (Nm•BwHt^{-1})	-0.04 (0.03)	-0.03 (0.02)	0.19	**-0.04 (0.03) ***	**-0.03 (0.02)***	0.06
E.S. EKAMp (Nm•BwHt^{-1})	**-0.10 (0.05)***	**-0.06 (0.05)***	0.06	**-0.10 (0.05) ***	**-0.06 (0.06)***	0.02
L.S. EKAMp (Nm•BwHt^{-1})	**-0.05 (0.05)***	**-0.03 (0.03)***	0.17	**-0.05 (0.05) ***	**-0.03 (0.03)***	0.12
EKAMp timing (%stance)	-3.0 (14.3)	10.8 (12.2)	0.002 *	**-2.2 (14.4)**	**9.2 (13.6)***	0.01
E.S. EKFMp (Nm•BwHt^{-1})	-0.02 (0.10)	-0.03 (0.12)	0.68	-0.02 (0.11)	-0.02 (0.11)	0.91
Peak trunk angle (deg)	**11.1 (5.9)***	**7.8 (7.8)***	0.12	**10.7 (6.1) ***	**8.6 (7.9)***	0.32
Trunk angle at EKAMp (deg)	**9.8 (7.4)***	**7.4 (8.2)***	0.33	**9.9 (6.7) ***	**7.3 (9.4)***	0.29
Peak tibia angle (deg)	0.5 (2.7)	1.6 (3.0)	0.20	0.7 (2.7)	1.1 (3.1)	0.72
E.S. tibia angle ROM (deg)	1.2 (3.8)	1.5 (3.7)	0.85	1.2 (3.7)	1.6 (4.0)	0.76
Tibia angle at EKAMp (deg)	0.2 (3.1)	0.8 (2.8)	0.50	0.3 (3.0)	0.7 (3.0)	0.63
E.S. peak knee flexion (deg)	1.6 (5.5)	1.9 (5.4)	0.85	1.9 (5.5)	1.4 (5.5)	0.79
Gait speed (m/s)	**-0.14 (0.11)***	**-0.14 (0.14)***	0.99	**-0.15 (0.1)***	**-0.11 (0.12)***	0.33

EKAMp = EKAM peak, EKFMp = peak external knee flexion moment, E.S. = early stance, L.S. = late stance, angles are all determined in the frontal plane, *) significantly different relative to comfortable walking as determined by a paired t-test (after Bonferroni correction: $p \leq 0.00038$).

Appendix E. Overview of regression analysis outcomes

Model parameters	OR	95% CI	*p*	Nagelkerke R^2
EKAM peak reduction				
Early stance frontal tibia angle ROM	0.61	0.30 – 1.25	0.18	0.12
Early stance peak knee flexion angle	0.90	0.80 – 1.02	0.09	
EKAM impulse reduction				
Early stance frontal tibia angle ROM	1.69	0.82 – 3.47	0.15	0.06

Appendix F. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.02.017.

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