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Effect of real-time biofeedback on peak knee adduction moment in patients with medial knee osteoarthritis: Is direct feedback effective?

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ABSTRACT

Background: Gait modifications can reduce the knee adduction moment, a representation of knee loading. Reduced loading may help to slow progression of medial knee osteoarthritis. We aimed to investigate the response of patients with medial knee osteoarthritis to direct feedback on the knee adduction moment as a method for modifying the gait pattern, before and after training with specific gait modifications.

Methods: Forty patients with medial knee osteoarthritis underwent 3D gait analysis on an instrumented-treadmill, while receiving real-time feedback on the peak knee adduction moment. Patients were trained with three different modifications; toe-in, wider steps and medial thrust gait. The response to real-time feedback on the knee adduction moment was measured before and after training. To evaluate the short term retention effect, we measured the changes without feedback. We also evaluated the effects on the knee flexion moment and at the hip and ankle joints.

Findings: With direct feedback on the knee adduction moment, patients were initially unable to reduce the knee adduction moment. After training with specific modifications, peak knee adduction moment was reduced by 14% in response to direct feedback. Without feedback a 9% reduction in peak knee adduction moment was maintained. Hip moments were not increased with modified gait, but small increases in ankle adduction moment and knee flexion moment were observed.

Interpretation: Real-time biofeedback directly on the knee adduction moment is a promising option for encouraging gait modifications to reduce knee loading, however only when combined with specific instructions on how to modify the gait.

1. Introduction

Progression of medial knee osteoarthritis (OA) has been associated with an increased knee adduction moment, KAM (Bennell et al. 2011; Chang et al. 2015; Miyazaki et al. 2002; Morgenroth et al. 2014). KAM is generally accepted as a representation of the medial compartment knee load that correlates to direct measurement of contact forces in the knee (Zhao et al. 2007) and is associated with changes in cartilage integrity (Bennell et al. 2011; Miyazaki et al. 2002). Conservative treatments for knee osteoarthritis often target a reduction in KAM (Reeves and Bowling 2011).

Gait modifications may reduce KAM in persons with medial knee osteoarthritis (mKOA) (Simic et al. 2011) with associated reductions in pain and improvements in functional ability (Hunt and Takacs 2014; Shull et al. 2013b). Real-time biofeedback has increasingly been used to teach the gait modifications; but to date only in a small number of studies with OA patients (Hunt and Takacs 2014; Hunt et al. 2011; Shull et al. 2013a; Shull et al. 2013b). Optimal real-time biofeedback methods for training the modifications and hence reducing KAM remain unknown, particularly given the heterogeneity between studies (Richards et al. 2017).

Biofeedback used during gait retraining in mKOA patients often focuses on specific kinematic parameters that are generally understood to influence the KAM (Hunt and Takacs 2014; Hunt et al. 2011; Shull et al. 2013a, 2013b; Simic et al. 2011). In studies with healthy controls, however, greater reductions in KAM were noted when patients were able to define their own gait modifications in response to feedback on the KAM itself (van den Noort et al. 2015; Wheeler et al. 2011). In this

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study, we term this direct feedback (that is feedback on the parameter that we are trying to modify). The effectiveness of direct feedback for reducing KAM in healthy controls is in keeping with studies in healthy subjects and sports persons which show that people generally perform better at a specific motor task when provided with feedback on the end result rather than feedback on the intermediate steps (Wulf 2013). Use of direct KAM feedback for reducing the KAM has, to the best of our knowledge, not been investigated in mKOA patients.

Biofeedback using indirect feedback (i.e. feedback that is not on the KAM itself, but on a parameter assumed to influence the KAM), requires a priori knowledge about the relationship between the modified variable and the reduction in the KAM. Research in healthy controls (Favre et al. 2016) has shown that there is an individual dose-response relationship (change in modified variable vs. reduction in KAM), which is also likely to be true in the KOA population. Furthermore, personal preferences also play a key role in determining an effective gait modification strategy (Gerbrands et al. 2014; Gerbrands et al. 2017). Gait compensations may also play a role, resulting in ineffective KAM reduction. The problem of prescribing specific modifications may be avoided through use of direct feedback allowing patients to apply their own gait modification strategy.

Allowing patients to select their own gait modifications, may have some benefits over using prescribed modifications. However, this strategy may also result in modifications which reduce gait energy efficiency or increase loads on other joints of the lower limb or trunk. When instructed to lower their KAM without being provided with additional instructions some (healthy control) subjects adopted exhibited extreme modifications (van den Noort et al. 2015) which may have adverse biomechanical consequences (at other joints). It is important therefore to evaluate the loading at the hip and ankle joints. A recent study by Gerbrands et al. 2017 using increased trunk lean and medial knee thrust gait did not report increases in the hip and/or ankle joint moments. Nevertheless, the effect of self-defined gait modifications on the hip and ankle joint moments remains an important unanswered question.

The aim of this study, therefore, was to investigate the response of mKOA patients to direct feedback on the knee adduction moment, in terms of reduction in the first peak KAM, during steady state treadmill walking, before and after receiving specific kinematic instructions. We hypothesized that, as shown in healthy controls (van den Noort et al. 2015; Wheeler et al. 2011), mKOA patients would be able to modify their gait to reduce the KAM in response to direct KAM feedback. Further we hypothesized that, after being trained using specific kinematic methods for reducing the KAM, patients would further reduce the KAM and maintain their selected gait modifications when feedback was removed. Finally, we hypothesized that these changes would not result in increased joint moments at the hip and ankle.

2. Methods

2.1. Patients

Forty patients with symptomatic mKOA were recruited through advertisements in local newspapers and a national patient oriented e-magazine as well as from a local rehabilitation centre (Reade, center for rehabilitation and rheumatology, Amsterdam, the Netherlands). Ethical approval was provided by the VUmc Medical Ethical Committee and patients provided written informed consent prior to participation.

This study was powered on the KAM, with an anticipated effect size of 0.45 ($\alpha = 0.05$ and $\beta = 0.2$) based on similar studies (Hunt and Takacs 2014; Shull et al. 2013b). Inclusion criteria were radiographic evidence of mKOA with KL (Kellgren & Lawrence) Grade 1 or higher, aged between 50 and 75 and ability to walk unaided for at least 30 min. Predominant lateral or patella-femoral osteoarthritis, previous or planned hip or knee replacement, hip or ankle arthritis, rheumatoid arthritis and BMI > 35 were exclusion criteria. Patients attended the Virtual Reality Lab at the VUmc for a single measurement session.

2.2. Pain and functional assessment

Prior to the measurement, patients completed the Western Ontario and McMaster Universities Arthritis (WOMAC) questionnaire (Bellamy and Buchanan 1986) and rated their pain in the past week and on the day of assessment using the numeric rating scale (NRS) from 0 to 10 where 0 represents no pain and 10 the highest level of pain.

2.3. Preparation for gait trials

Reflective markers were placed on the lower limbs and trunk of the patients according to the local protocol, based on Cappozzo et al. 1995 The following locations were used for anatomical markers: first, second and fifth metatarsal head, calcaneus (rear aspect), medial and lateral malleoli, tibial tuberosity, head of the fibula, medial and lateral epicondyles, anterior and posterior superior iliac spine, navel, xyphoid process, jugular notch, 7th cervical vertebrae and 10th thoracic vertebrae. Additional markers were affixed on each segment as necessary for tracking purposes.

After preparation, a static calibration trial was recorded with the patient standing in a neutral position. During all trials, marker trajectories were captured at 100 Hz using a 10-camera motion capture system (Vicon, Oxford Metrics Group, Oxford, UK). Forces were recorded at 1000 Hz using two force plates embedded within a split belt treadmill (MOTEK ForceLink BV, Amsterdam, NL). Feedback was provided on a 180-degree screen positioned in front of the patient; experimental set-up presented in Fig. 1.

2.4. Data processing

Data were processed using an in-house developed biomechanics software to calculate joint angles and moments (BodyMech, Amsterdam, NL Matlab-based). Marker position data were filtered at 6 Hz to remove high frequency artefacts. Force data were filtered at 10 Hz with a second order bi-directional filter. A force threshold of 25 N was used to establish gait events. Joint moments were calculated using inverse dynamics with the joint moments expressed in the distal reference frame.

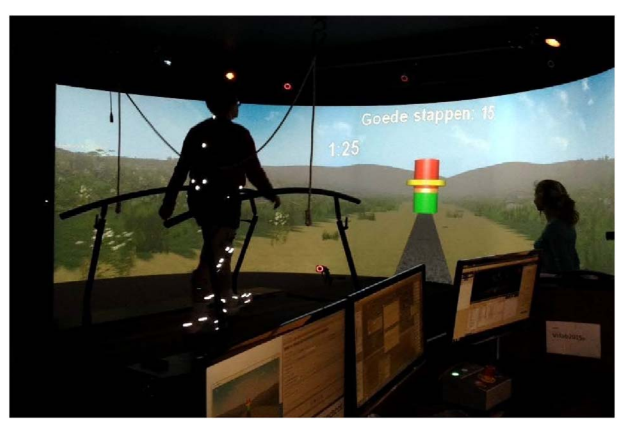

Fig. 1. Experimental set up used for the investigation. Subjects walked on the split belt treadmill while a virtual reality environment was projected onto a 180° screen in front of them. The yellow bar in the centre of the screen moved up and down with the height corresponding to the average KAM value over the first peak of the preceding step. The green region represented the target KAM, 10% reduction from baseline, and the red represented KAM above the baseline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Gait trials, in order of measurement.

Trial	Instruction to patient	Type of feedback	Description of trial and justification
Baseline/natural walking	Try to walk comfortably as if you were walking around your local neighbourhood.	No feedback	Normal gait pattern without any modification required for comparison with other trials and used to set the 10% KAM reduction for the following trials.
Direct feedback on KAM (1st): visual	Try to walk in such a way that the yellow band (on screen) moves into the green region (Fig. 2a). The yellow band represents the load on the medial side of your knee when you are standing on it. If you reduce this by 10% or more the yellow band will move into the green region and if you increase it by 10% or more, the band will move into the red region. You can try lots of different ways of walking to see if you can find a successful modification.	Visual feedback (Fig. 1) with target reduction of 10% below KAM baseline level (calculated as an average over the first peak)	To assess how patients respond to direct feedback before being provided with any specific instructions on how to change their gait pattern.
Direct feedback on KAM: audio	Try to walk in such a way that you hear no sound. A high sound indicates that the load (KAM) is greater than your baseline and a lower pitch indicates that the load (KAM) is between 90 and 100% of baseline values. No sound indicates a 10% or greater reduction in the loading (KAM).	Audio feedback with target reduction as in previous trial.	Trial used to assess patient's response to audio feedback. Allows assessment of patients preference for audio/visual feedback
Direct feedback on KAM: visual (2nd)	As previously, try to walk in such a way that the yellow band remains within the green region. You may use one or a combination of the previously tried gait modifications from the training section in order to attempt this.	As described previously (trial 2)	To assess how patients respond to direct feedback on the KAM after being trained with three specific gait modifications and to assess which (combination of) modifications were preferred.
Retention phase	Try to retain the learnt gait modifications while walking. You may use one or a combination of the previously tried gait modifications; whichever you find most comfortable.	No feedback	This trial is conducted after a break of 10 to 15 min to assess the short term retention of the gait pattern.

2.5. Gait trials

Patients acclimatized on the treadmill for at least 3 min. Comfortable walking speed was determined by incrementing the speed slowly until the speed was agreed by the patient. Following this, a series of two-minute gait modification trials were recorded (at fixed speed) as described in Table 1. The first trial was a baseline trial, to measure the normal gait kinematics and kinetics. Following this, patients were provided with direct KAM feedback on first peak KAM initially in a visual format (Fig. 2 a) and in an audio format. Patients were then trained with three specific kinematic modifications; toe-in gait, wider steps and medialisation of the knee position, (biomechanical rationale and patient instructions provided in Table 2; visual feedback provided in Fig. 2). The order for these kinematic modifications was fixed to standardize the method for all patients. Furthermore, we wanted to encourage patients to combine modifications in the following trial with direct feedback on the KAM. The order in which we taught the modifications was considered the most logical order for patients to combine two or more modifications. Data from the training section were also recorded but are not presented in this paper.

A target reduction of 10% for the first peak KAM was decided upon based on previous studies showing that this is achievable without

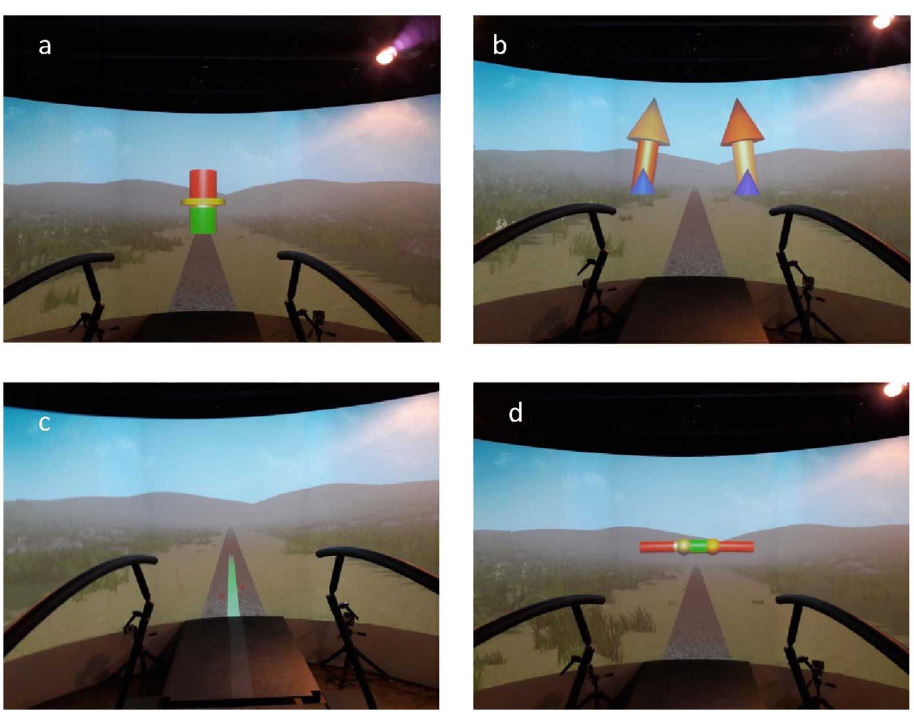

Fig. 2. Patients were presented with different kinds of (visual) feedback during the trials. a) Direct feedback on the first peak KAM, b) feedback on foot progression angle (toe-in), c) feedback on step width, d) feedback on position of the knees in the frontal plane.

Table 2
Training trials with specific gait modifications; description and justification of trial.

Modification	Description of training method	Biomechanical rationale for the modification
Toe in gait	Patients were asked to walk with their feet turned in more than normal. An on-screen target was provided to guide patients. This target angle was set based on the foot progression angle in the preceding KAM feedback trial: in the case that patients succeeded in reducing the KAM by 10% or more using a toe-in gait strategy, the target angle was set to the mean angle during that trial. If the reduction was < 10%, the target angle was set to the foot progression during the KAM feedback trial plus up to 10° depending on the percentage reduction in the KAM feedback trial. Whilst some previous studies have preferred to use the same target for all subjects (either a relative or absolute target), we considered that this was not the optimal based on the findings of Favre et al. who show that there is an individual dose response relationship (Favre et al. 2016).	Increasing the internal rotation of the foot with respect to the direction of travel (walking with toes in) has the effect of shifting the centre of pressure laterally since the heel of the foot is now externally rotated, thereby reducing the moment arm from the centre of pressure to the knee joint centre during the first double support period. The knee itself also rotates inwards during this movement (Shull et al. 2013a).
Feedback on step width	Visual feedback with target step width projected on screen, and position of patients' feet shown relative to the target. As described above the target step width was set based on the reduction in KAM in the direct KAM feedback trial. If the patient succeeded in reducing the KAM in the direct KAM feedback trial by increasing his/her step width then the target step width was set to match that in the direct KAM feedback trial. Otherwise the step width target was set to the baseline step width plus an increment of between 3 and 8 cm depending on the percentage KAM reduction during the direct KAM feedback trial.	Increasing the step width lateralizes the centre of pressure, allowing the ground reaction force to pass closer to the knee joint centre (Fregly et al. 2008)
Feedback on medial knee position	Visual feedback with target knee position projected on screen and actual position of knees shown relative to the target. Patients were instructed to bring their knees closer together during the stance phase, while trying to avoid an excessive increase in knee flexion. As previously the target distance was defined based on the KAM visual feedback trial. If the patient was successful in reducing the KAM during the direct feedback trial using a change in the knee frontal plane position (i.e. medial knee thrust), then the target was set to the distance used during the direct KAM feedback trial. If this was not the case, the target distance was decreased by up to 5 cm depending on the percentage reduction during the direct KAM feedback trial. Note: targets were set separately without combining the modifications.	Increasing medial knee thrust reduces the knee varus angle and hence decreases the frontal plane moment arm.

requiring excessive gait modifications (Hunt and Takacs 2014; Shull et al. 2013b). Patients were verbally discouraged to use trunk lean. Although this has been shown to be an effective technique for reducing the KAM by re-directing the line of action of the force, excessive trunk lean may result in increased trunk loading and lower back pain (Nuesch et al. 2016). Patients rested between trials if required and the feedback for the next trial was demonstrated to the patient during this time. The first 30s of each trial was performed at a reduced speed (80% of the original speed) to allow a short practice period. Following this data were recorded for 90 s at the original speed (as used in the baseline trial). Standardized instructions were provided to patients prior to each trial (Table 1). Feedback was provided on the KAM of the most affected leg only for simplification. However, patients were encouraged to perform bilateral gait modifications. Relevant kinematic and kinetic variables were calculated using the Human Body Model (van den Bogert et al. 2013) during the trials for use in the real-time feedback (D-Flow).

2.6. Statistical analysis

Descriptive statistics were used to characterize the study population. Prior to statistical analysis, outcome measures were assessed for normality with Shapiro–Wilk and Kolmogorov-Smirnov tests.

For all patients ($n = 40$) and each condition (5) several kinetic, kinematic and spatio-temporal parameters were extracted from each complete gait cycle. All gait cycles were included, with the exception of those where the patient stepped onto both force plates with one foot. The primary parameters of interest were first peak KAM, peak KFM and KAM impulse. Secondary parameters were maximum sagittal and frontal plane moments at the hip, and ankle. Furthermore, we analysed the foot progression angle at the first peak KAM, the frontal plane distance between the mid-pelvis and the knee joint centre and the step width.

Paired *t*-tests were used to check for inter-leg differences and the Wilcoxon signed rank test was used for data with non-normal distribution. Between-condition differences in the joint moments for the feedback leg only (parameters as listed above) were evaluated using within subject, repeated measures analysis of variance with Greenhouse-Geisser correction applied as required. Post-hoc tests were conducted with Bonferroni correction for multiple comparisons and in line with our hypotheses assessed differences in the variables of interest between baseline and feedback trials. Data with a non-normal distribution were tested using the Friedman test and post hoc tests using the Wilcoxon signed rank test. All analyses were performed using SPSS software, version 22.0 (SPSS, Chicago, IL, USA) with $\alpha = 0.05$.

3. Results

3.1. Demographics and patient reported outcome measures

Forty patients participated in the study (25 female); demographics presented in Table 3. The age range represents the normal age range for primary mKOA. The majority of patients had mild to moderate mKOA (KL scores 1 to 2). WOMAC scores for pain, function and stiffness were generally low (Table 4) with some patients reporting no pain or difficulty during normal daily activities. Baseline NRS pain was low (mean 3.05 out of 10). In standing, the group mean frontal plane knee angle indicated a near neutral position for both legs (mean angle 0.74 and 0.52° respectively).

3.2. Gait parameters – changes in joint moments

Group mean values for the frontal and sagittal plane knee moments for the feedback leg are presented in Fig. 3. The data analysis considered only the feedback leg since no significant differences in peak moments were observed between the feedback leg and the contralateral leg; (Supplementary Table 1).

Table 3
Demographics of participants included in the study.

Characteristic	Mean (SD)	Range
Age (yr)	61.7 (6.0)	51.0–71.7
Height (m)	1.73 (0.10)	1.53–2.00
Mass (kg)	77.2 (11.0)	57.2–104.7
BMI (kg/m^2)	25.6 (2.5)	20.0–33.7
Gender	M 15 F 25	
Number of years with self-reported knee pain	11.2 (9.6)	0.5–42.0
Kellgren and Lawrence Grade (of the knee on which feedback was provided; the knee where the subject reported most complaints)	I: 19, II: 8, III: 9, IV: 4.	
Static varus/valgus angle[a] (°)	Feedback leg 0.74 (3.71) Contralateral leg 0.52 (4.28)	

[a] calculated from the standing position during the calibration trial (not based on x-rays).

Table 4
Patient reported outcome measures.

Characteristic	Mean (SD)	Range
WOMAC – pain (max. 20)	5.35 (3.13)	0–15
WOMAC – function (max. 68)	19.10 (12.08)	1–50
WOMAC – stiffness (max. 8)	3.25 (1.96)	0–8
Baseline pain at time of the assessment (scale from 0 to 10)	3.05 (2.16)	0–7

Use of gait modifications resulted in statistically significant within-subject changes in KAM ($P < 0.001$), KFM ($P < 0.001$), KAM impulse ($P < 0.001$), and ankle adduction moment, AAM, ($P < 0.001$).

First peak KAM was significantly reduced with respect to baseline walking when patients received visual feedback on the KAM after training with specific kinematic instructions (14.28% reduction, $P < 0.001$). This reduction was partly maintained during the retention trial (8.81% reduction, $P = 0.003$); Table 5. Peak KFM was significantly increased w.r.t. baseline during the second KAM visual feedback trial (21.6% increase, $P = 0.005$) and the retention trial (14.6% increase, $P = 0.045$). KAM impulse was significantly reduced during the second KAM visual feedback trial (19.81% reduction, $P < 0.001$) but was not maintained in the retention trial ($P = 0.203$). Stance time was not significantly different between the baseline and KAM feedback trials ($P > 0.522$).

Use of gait modifications did not result in significant changed in the hip adduction moment ($P = 0.083$). Similarly, peak HFM was not significantly changed through walking with gait modifications ($P = 0.182$). Peak AAM was significantly increased compared to baseline during the second KAM visual feedback trial and the final retention trial ($P < 0.001$). There were no significant changes in the peak ankle flexor moment for any condition ($P > 0.058$).

3.3. Gait parameters – key kinematic/spatio-temporal parameters

No significant differences were observed between the foot progression angle (FPA) of the feedback leg and the contralateral leg (Supplementary Table 2) for any of the conditions investigated in this study ($P > 0.05$). Compared to baseline FPA was significantly more internally rotated, during the second KAM visual feedback and retention trials $p < 0.001$ (Table 6).

Compared to the baseline condition, patients significantly increased their step widths during all trials, with large increases (median increase of 8.69 cm and 6.45 cm, $P < 0.001$) during the second visual feedback and retention trials; Table 6.

The frontal plane position of the knees was significantly different w.r.t. baseline condition during the second KAM visual feedback condition and the retention trial (increase of 0.5 cm in both conditions, $P = 0.006$ and $P = 0.003$ respectively).

4. Discussion

4.1. Effects on the knee moments

Patients with mKOA were initially unable to modify, their gait to reduce first peak KAM in response to direct feedback on the KAM itself, unlike healthy controls (van den Noort et al. 2015; Wheeler et al. 2011). Wheeler et al. (2011) provided participants with some suggestions on how to modify their gait, whereas van den Noort et al. (2015) did not provide such suggestions. Therefore, the first trials in our study are only directly comparable to the study of van den Noort et al. (2015) and not to Wheeler et al. (2011). A further important difference is that the subjects in both of these studies were young and non-arthritic, whereas in our study all participants had confirmed mKOA and were above the age of 50. Literature in other fields has shown that direct feedback on the parameter of interest may be superior to feedback on an intermediate parameter, as it increases motor learning and improves retention of the learnt skill (Wulf 2013; Wulf and Su 2007). In our cohort of patients use of direct feedback, without any suggestions of how to modify the gait pattern, was not effective in significantly reducing. Patients also reported frustration when presented with direct feedback, in particular audio feedback. We present analysis of the effects across multiple (> 60) cycles per trial (all applicable cycles within a 90 s window). Post-hoc testing using only the last 20 cycles from the direct feedback trials showed no significant differences in the KAM in these last 20 cycles ($p > 0.05$). Even during the last 20 steps it appeared that patients had not converged on a consistently successful strategy.

After being provided with specific training on three different kinematic modifications which can reduce KAM, first peak KAM was reduced by 14%, comparable to the reduction in first peak KAM observed after six weeks toe-in gait training in 10 mKOA patients, 14.3% (Shull et al. 2013b). In general patients used a combination of toe in gait and increased step width together with the direct feedback on KAM during successful trials. Due to the individual dose response relationship (as indicated in healthy controls (Favre et al. 2016)), direct feedback may be preferential to feedback on a variable assumed to influence the KAM; this avoids the situation where a subject performs the prescribed kinematic modification perfectly but does not reduce the KAM due to compensations elsewhere or due to a non-linear relationship between change in kinematic modification and KAM reduction. In general patients in this study who reduced the first peak KAM during the KAM feedback trial (after training) also reduced the KAM impulse, a parameter which has been strongly associated with progression of KOA (Bennell et al. 2011). That the reduction in KAM impulse was not maintained during the (short term) retention trial suggests that the patients could not fully replicate the learnt gait modifications after a short break, despite maintaining some reduction in the first peak KAM.

Peak KFM, which may contribute significantly to the overall knee contact forces (Creaby 2015) was significantly increased in comparison to baseline during the second KAM visual feedback trial (after training) and during the retention trial, caused by an increase in knee flexion. KFM contributes to increased knee loading by increasing eccentric muscle force in the quadriceps (Creaby 2015). Small increases in KFM may be acceptable, where there is a larger decrease in KAM since modeling studies have shown that changes in the total contact force are primarily driven by changes in KAM, with a lesser contribution from the KFM (Manal et al. 2015).

In this study patients experimented with different gait modifications whilst being presented with direct feedback on KAM which allowed them to observe directly the effect of small changes in gait on the KAM. Using this method, we predicted that patients would be able to determine their own combination of modifications. However, patients

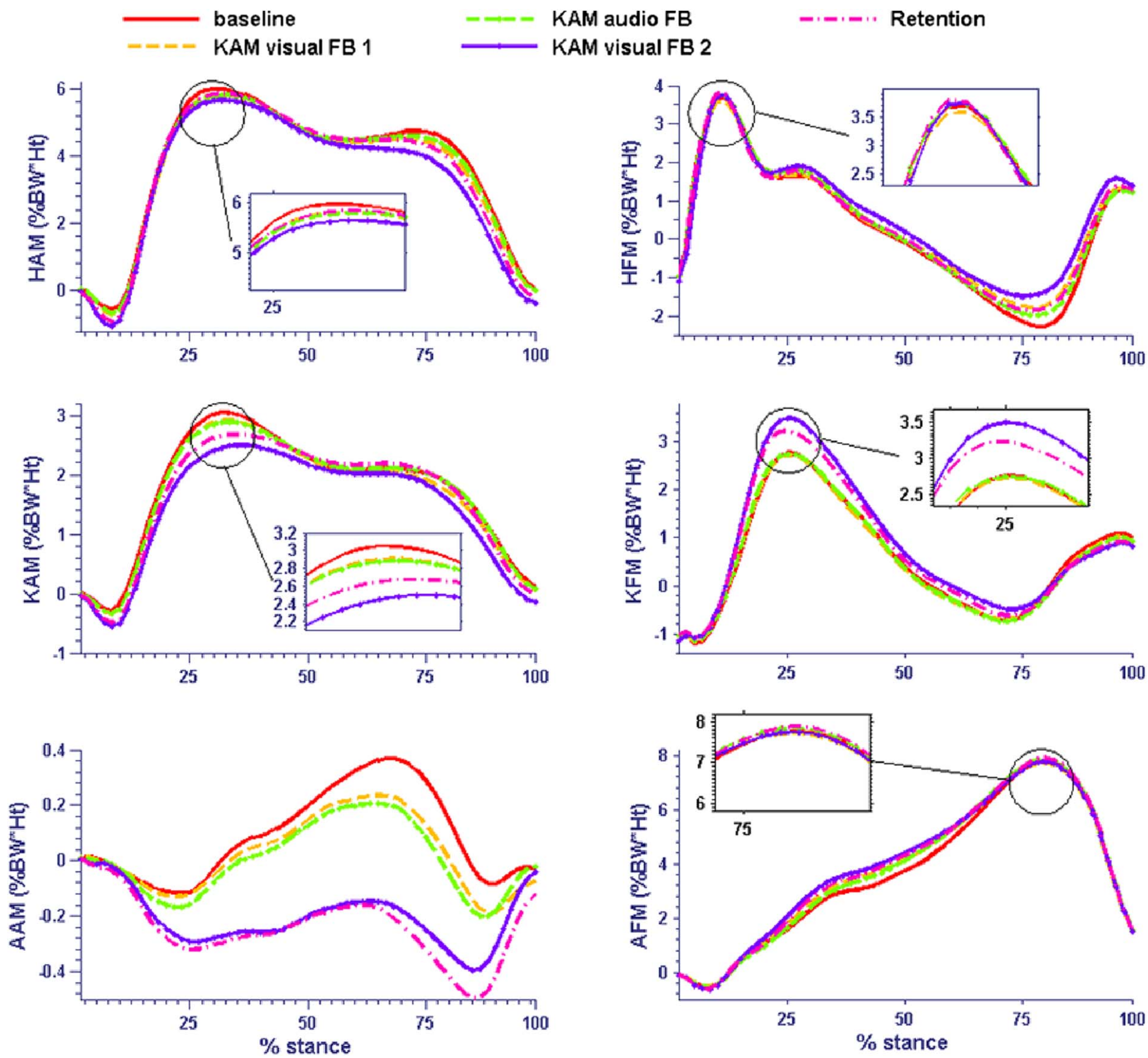

Fig. 3. Mean frontal (left hand column) and sagittal plane joint moments on most affected side (top hip moments, middle knee moments and bottom ankle moments).

were initially unable to develop a strategy to consistently reduce KAM before being given training on specific gait modifications. We investigated audio as well as visual feedback since it could be a more convenient option for training outside of the laboratory environment; however, the majority of patients preferred the visual format. Reduction of KAM was similar in both conditions. After receiving instructions on three potential modifications, patients were able to successfully modify their gait when guided by KAM feedback. This is an important finding which could be useful for future studies, employing direct KAM feedback in place of prescribed kinematic modifications, where the dose response relationship is variable between subjects (Favre et al. 2016). Furthermore a prescribed change in a kinematic parameter may not decrease peak KAM because of compensations in other joints; for example in the study of (van den Noort et al. 2015) subjects performed a hip internal rotation gait strategy but did not reduce the peak KAM. Provision of direct feedback on KAM combined with specific suggestions on how to modify the gait may also accelerate the learning process and help in applying the modification(s) outside of the lab. However, subjects may also find it difficult to remember the required combination of gait modifications and therefore may struggle to maintain the modifications in activities of daily life.

4.2. Effects of gait modifications on the hip and ankle moments

Previous studies on gait retraining in mKOA patients have largely neglected the effects of modifications at the hip and ankle joints. However, changes in hip joint moments in both the contralateral and ipsilateral have been reported with use of a knee unloading brace (Toriyama et al. 2011). Reductions in KAM causing increased hip adduction moment may increase loading at the hip; a risk factor for development of hip OA (Aresti et al. 2016). In comparison with baseline condition, we found no significant increases in either the hip frontal or sagittal plane moments (HAM and HFM), suggesting no contra-indications for this type of training regarding risk of increased loading at the hip. Significant changes in the peak AAM were noted during the final two trials. The clinical relevance of this change is unclear, given the small changes in absolute values. Importantly AFM was not reduced, which may be an important factor, in order to maintain the required power generation for initiation of the next step.

4.3. Limitations of this study

All training and measurements were carried out on a treadmill. This may influence the perception of dynamic balance of patients and hence the ability to modify their gait. Treadmill walking can also result in

Table 5
Knee adduction and flexion moments across different trial conditions.

Condition	First Peak Adduction moment, KAM (% BW∗Ht) (SD)	P (comparison with baseline value)	Adduction moment impulse (% BW∗Ht∗s), KAMi(SD)	P (comparison with baseline value)	Peak flexor moment, KFM (% BW∗Ht) (SD)	P (comparison with baseline value)
Baseline (no feedback)	3.29 (1.00)	–	1.11 (0.51)	–	3.15 (1.10)	–
Visual Feedback on first peak KAM (1st)	3.19 (1.04)	0.149	1.04 (0.53)	0.140	3.13 (1.15)	1.000
Audio Feedback on first peak KAM	3.18 (0.94)	0.056	1.08 (0.53)	1.000	3.16 (1.16)	1.000
Visual Feedback on first peak KAM (2nd)	**2.82 (0.71)**	< **0.001**	**0.89 (0.46)**	< **0.001**	**3.83 (1.49)**	**0.005**
Retention (no feedback)	**3.00 (0.77)**	**0.003**	1.02 (0.47)	0.203	**3.61 (1.48)**	**0.045**

Values in bold significant at $\alpha = 0.05$.

Table 6
Foot progression angle, step width and knee separation distances across different trial conditions.

Condition	Median (IQR) step width[a] (m)	P (comparison with baseline value)[c]	Mean (SD) foot progression angle at first peak KAM (°)[b]	P (comparison with baseline condition)	Knee frontal plane position relative to centre pelvis (mean (SD) distance from centre pelvis to knee joint centre at first peak KAM) (cm)	P (comparison with baseline condition)
Baseline (no feedback)	0.132 (0.050)	–	− 5.65 (4.76)	–	9.33 (1.24)	
Visual Feedback on first peak KAM	**0.135 (0.05)**	**0.007**	− 4.83 (5.06)	0.426	9.41 (1.29)	1.00
Audio Feedback on first peak KAM	**0.134 (0.05)**	**0.009**	− 4.23 (5.40)	0.087	9.25 (1.38)	1.00
Visual Feedback on first peak KAM	**0.212 (0.04)**	< **0.001**	0.18 (5.60)	< **0.001**	**9.86 (1.41)**	**0.008**
Retention (no feedback)	**0.197 (0.04)**	< **0.001**	0.61 (6.50)	< **0.001**	**9.84 (1.40)**	**0.005**

Values in bold significant at $\alpha = 0.05$.
[a] Distance between ipsi- and contralateral heel markers at initial contact of the ipsilateral foot.
[b] Positive angle represents toe-in, negative angle represents toe-out.
[c] Non-parametric testing used.

small differences in gait kinematics and kinetics, compared to overground walking (Riley et al. 2007). However treadmill-based data collection provides the benefit of collecting large quantities of kinetic data while additionally allowing a consistent walking speed; a potential confounding factor.

In this study, we present results from gait training during a single-session. Reduction in KAM peak was statistically significant; however whether this equates to a clinically significant change remains unknown. There is currently no agreed level for a clinically significant change in KAM, with reductions following high tibial osteotomy of > 50% (Bhatnagar and Jenkyn 2010) compared to < 15% from knee unloader braces (Lindenfeld et al. 1997; Pollo et al. 2002). Increased training time is likely to be necessary for retention of the modifications and to facilitate continued reduction of KAM outside the lab. Future controlled trials with assessment of both patient reported outcome measures and changes in cartilage thickness alongside changes in the knee joint moments, over a longer period are ultimately required to evaluate clinical and radiographic benefits of such gait modifications.

When providing training with specific modifications to the patients in our study, we chose not to randomize the order of the modifications but instead to provide the feedback in a standardized order for each patient. This may have resulted in a bias in the outcomes in the following trials.

Finally, we focused on reducing peak KAM despite continuing ambiguity surrounding the relationship between KAM and the medial contact force (Walter et al. 2010). Future studies in this area are encouraged to use musculoskeletal modeling to investigate the changes in the joint contact forces as a result of such gait modifications.

In conclusion, patients with mKOA required a short training period where they were provided with specific kinematic instructions, before they could effectively reduce the KAM in response to direct KAM feedback. Used in combination with specific instructions on how to modify the gait, direct KAM feedback was effective. Short term retention of the effect on peak KAM was shown when patients walked without receiving feedback on their gait pattern, albeit with a smaller effect size. Future work should focus on maintaining this reduction over a longer time period and implementing such training in clinical practice. Importantly, for clinical adoptability, the gait modifications selected by the patients did not result in increased loading at the hip in either the sagittal or frontal plane, with statistically significant, but small absolute changes noted at the ankle. Finally, our results support the idea of individual dose-response relationships between changes in kinematics and changes in kinetics in patients with knee OA. Further investigation of these relationships is required for optimization of such training programs.

Competing interest statement

There are no conflicts of interest to report.

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Appendix A. Supplementary data

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References

Aresti, N., Kassam, J., Nicholas, N., Achan, P., 2016. Hip osteoarthritis. BMJ 354, 1–10.
Bellamy, N., Buchanan, W.W., 1986. A preliminary evaluation of the dimensionality and clinical importance of pain and disability in osteoarthritis of the hip and knee. Clin. Rheumatol. 5, 231–241.
Bennell, K.L., Bowles, K.A., Wang, Y., Cicuttini, F., Davies-Tuck, M., Hinman, R.S., 2011. Higher dynamic medial knee load predicts greater cartilage loss over 12 months in medial knee osteoarthritis. Ann. Rheum. Dis. 70, 1770–1774.
Bhatnagar, T., Jenkyn, T.R., 2010. Internal kinetic changes in the knee due to high tibial osteotomy are well-correlated with change in external adduction moment: an osteoarthritic knee model. J. Biomech. 43, 2261–2266.
van den Bogert, A.J., Geijtenbeek, T., Even-Zohar, O., Steenbrink, F., Hardin, E.C., 2013. A real-time system for biomechanical analysis of human movement and muscle function. Med. Biol. Eng. Comput. 51, 1069–1077.
Cappozzo, A., Catani, F., Croce, U.D., Leardini, A., 1995. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clin. Biomech. 10 (4), 171–178.
Chang, A.H., Moisio, K.C., Chmiel, J.S., Eckstein, F., Guermazi, A., Prasad, P.V., Zhang, Y., Almagor, O., Belisle, L., Hayes, K., Sharma, L., 2015. External knee adduction and flexion moments during gait and medial tibiofemoral disease progression in knee osteoarthritis. Osteoarthr. Cartil. 23, 1099–1106.
Creaby, M.W., 2015. It's not all about the knee adduction moment: the role of the knee flexion moment in medial knee joint loading. Osteoarthr. Cartil. 23, 1038–1040.
Favre, J., Erhart-Hledik, J.C., Chehab, E.F., Andriacchi, T.P., 2016. A general scheme to reduce the knee adduction moment by modifying a combination of gait variables. J. Orthop. Res. 34, 1547–1556.
Fregly, B.J., Reinbolt, J.A., Chmielewski, T.L., 2008. Evaluation of a patient-specific cost function to predict the influence of foot path on the knee adduction torque during gait. Comput. Methods Biomech. Biomed. Eng. 11, 63–71.
Gerbrands, T.A., Pisters, M.F., Theeven, P.J.R., Verschueren, S., Vanwanseele, B., 2017. Lateral trunk lean and medializing the knee as gait strategies for knee osteoarthritis. Gait Posture 51, 247–253.
Gerbrands, T.A., Pisters, M.F., Vanwanseele, B., 2014. Individual selection of gait retraining strategies is essential to optimally reduce medial knee load during gait. Clin. Biomech. 29, 828–834.
Hunt, M.A., Simic, M., Hinman, R.S., Bennell, K.L., Wrigley, T.V., 2011. Feasibility of a gait retraining strategy for reducing knee joint loading: increased trunk lean guided by real-time biofeedback. J. Biomech. 44, 943–947.
Hunt, M.A., Takacs, J., 2014. Effects of a 10-week toe-out gait modification intervention in people with medial knee osteoarthritis: a pilot, feasibility study. Osteoarthr. Cartil. 22, 904–911.
Lindenfeld, T.N., Hewett, T.E., Andriacchi, T.P., 1997. Joint loading with valgus bracing in patients with varus gonarthrosis. Clin. Orthop. Relat. Res. 290–297.
Manal, K., Gardinier, E., Buchanan, T.S., Snyder-Mackler, L., 2015. A more informed evaluation of medial compartment loading: the combined use of the knee adduction and flexor moments. Osteoarthr. Cartil. 23, 1107–1111.
Miyazaki, T., Wada, M., Kawahara, H., Sato, M., Baba, H., Shimada, S., 2002. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. Ann. Rheum. Dis. 61, 617–622.
Morgenroth, D.C., Medverd, J.R., Seyedali, M., Czerniecki, J.M., 2014. The relationship between knee joint loading rate during walking and degenerative changes on magnetic resonance imaging. Clin. Biomech. (Bristol, Avon) 29, 664–670.
van den Noort, J.C., Steenbrink, F., Roeles, S., Harlaar, J., 2015. Real-time visual feedback for gait retraining: toward application in knee osteoarthritis. Med. Biol. Eng. Comput. 53, 275–286.
Nuesch, C., Laffer, D., Netzer, C., Pagenstert, G., Mundermann, A., 2016. Effect of gait retraining for reducing ambulatory knee load on trunk biomechanics and trunk muscle activity. Gait Posture 47, 24–30.
Pollo, F.E., Otis, J.C., Backus, S.I., Warren, R.F., Wickiewicz, T.L., 2002. Reduction of medial compartment loads with valgus bracing of the osteoarthritic knee. Am. J. Sports Med. 30, 414–421.
Reeves, N.D., Bowling, F.L., 2011. Conservative biomechanical strategies for knee osteoarthritis. Nat. Rev. Rheumatol. 7, 113–122.
Richards, R., van den Noort, J.C., Dekker, J., Harlaar, J., 2017. Gait retraining with real-time biofeedback to reduce knee adduction moment: systematic review of effects and methods used. Arch. Phys. Med. Rehabil. 98, 137–150.
Riley, P.O., Paolini, G., Della, C.U., Paylo, K.W., Kerrigan, D.C., 2007. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. Gait Posture 26, 17–24.
Shull, P.B., Shultz, R., Silder, A., Dragoo, J.L., Besier, T.F., Cutkosky, M.R., Delp, S.L., 2013a. Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis. J. Biomech. 46, 122–128.
Shull, P.B., Silder, A., Shultz, R., Dragoo, J.L., Besier, T.F., Delp, S.L., Cutkosky, M.R., 2013b. Six-week gait retraining program reduces knee adduction moment, reduces pain, and improves function for individuals with medial compartment knee osteoarthritis. J. Orthop. Res. 31, 1020–1025.
Simic, M., Hinman, R.S., Wrigley, T.V., Bennell, K.L., Hunt, M.A., 2011. Gait modification strategies for altering medial knee joint load: a systematic review. Arthritis Care Res.

63, 405–426.
Toriyama, M., Deie, M., Shimada, N., Otani, T., Shidahara, H., Maejima, H., Moriyama, H., Shibuya, H., Okuhara, A., Ochi, M., 2011. Effects of unloading bracing on knee and hip joints for patients with medial compartment knee osteoarthritis. Clin. Biomech. 26, 497–503.
Walter, J.P., D'Lima, D.D., Colwell Jr., C.W., Fregly, B.J., 2010. Decreased knee adduction moment does not guarantee decreased medial contact force during gait. J. Orthop. Res. 28, 1348–1354.
Wheeler, J.W., Shull, P.B., Besier, T.F., 2011. Real-time knee adduction moment feedback for gait retraining through visual and tactile displays. J. Biomech. Eng. 133, 041007.
Wulf, G., 2013. Attentional focus and motor learning: a review of 15 years. In: International Review of Sport and Exercise Psychology. Routledge, pp. 77–104.
Wulf, G., Su, J., 2007. An external focus of attention enhances golf shot accuracy in beginners and experts. Res. Q. Exerc. Sport 78, 384–389.
Zhao, D., Banks, S.A., Mitchell, K.H., D'Lima, D.D., Colwell, C.W., Fregly, B.J., 2007. Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. J. Orthop. Res. 25, 789–797.