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Decreasing the ambulatory knee adduction moment without increasing the knee flexion moment individually through modifications in footprint parameters: A feasibility study for a dual kinetic change in healthy subjects

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Gait retraining is gaining in interest to reduce loading associated to knee osteoarthritis (OA) progression. So far, interventions focused on reducing the peak knee adduction moment (pKAM) and it remains unclear if this can be done individually without increasing the peak knee flexion moment (pKFM). Additionally, while modifying foot progression angle (FPA) and step width (SW) is common, little is known about modifications in stride length (SL). This study aimed at characterizing the feasibility of a dual kinetic change, consisting in reducing the pKAM by at least 10% without increasing the pKFM. It also aimed to evaluate the added value of SL modifications in achieving the dual kinetic change. Gait trials with modifications in FPA, SW and SL were recorded for 11 young healthy subjects in a laboratory equipped with an augmented-reality system displaying instruction footprints on the floor. All participants achieved the dual kinetic change with at least one of the modifications. Seven participants achieved it with FPA modification, three with SW modification, and seven with SL modification. In conclusion, this study showed that it is feasible to achieve the dual kinetic change individually through subject-specific modifications in footprint parameters, suggesting that, in the future, gait retraining could aim for more specific kinetic changes than simply pKAM reductions. Modifying SL allowed achieving the dual kinetic change, stressing out the value of this parameter for gait retraining, in addition to FPA and SW. Finally, an augmented-reality approach was introduced to help footprint parameter modifications in the framework of knee OA.

1. Introduction

Knee osteoarthritis (OA) is one of the most common causes of disability and pain worldwide. For instance, it is estimated that more than a fifth of the persons aged 65 or above suffer from symptomatic knee OA (Jordan et al., 2007), with medial-compartment knee OA being the most frequent form of the disease (Ahlbäck, 1968). While the pathogenesis of knee OA is still not fully understood, ambulatory mechanics has been shown to be an important factor in disease progression due to the repetitive loading of the joint (Andriacchi and Favre, 2014; Favre and Jolles, 2016).

The knee adduction moment (KAM) during walking, a proxy for the medial-lateral distribution of loading at the knee (Schipplein and Andriacchi, 1991), has long been related to medial knee OA (Miyazaki et al., 2002). Specifically, its peak amplitude during the first half of stance (pKAM) has been associated with progression, severity and pain in medial knee OA (Chehab et al., 2014; Erhart-Hledik et al., 2015; Thorp et al., 2007). This association has motivated the design of a range of pKAM reduction interventions, ultimately aiming at decreasing the loading in the medial compartment (Reeves and Bowling, 2011). No target for pKAM reduction has yet been clearly defined. Nevertheless, prior works reporting pain improvement in patients with medial knee OA aimed for reductions of at least 10% (Butler et al., 2007; Richards et al., 2018a; Shull et al., 2013b).

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Among the approaches to reduce the pKAM, gait retraining, which consists in teaching new ways of walking to the patients, is particularly interesting because it is noninvasive and does not require the use of a device during daily life activities, such as insoles or braces. As summarized in Table 1, diverse gait retraining systems using biofeedback have been proposed to help individuals modify their walking patterns and the results are encouraging both biomechanically (Table 1) and clinically (Cheung et al., 2018; Richards et al., 2018a; Shull et al., 2013b). Nevertheless, this approach is emerging and many aspects need to be evaluated and potentially improved.

Originally, gait interventions for medial knee OA focused on reducing the pKAM. This focus was largely due to the limited degrees of freedom of prior options to modify gait, such as tibial osteotomies, insoles or braces (Reeves and Bowling, 2011; Hussain et al., 2016). Gait retraining is different as it has the potential to induce more complex changes than simply pKAM reductions. This is noteworthy because disease progression has also been associated with the peak amplitude of the knee flexion moment during the stance phase of walking (pKFM) (Chehab et al., 2014). Specifically, 5-year cartilage thinning was shown to be larger in OA knees with larger pKFM. Additionally, since medial-compartment loading has been related to both the pKAM and the pKFM (Manal et al., 2015; Walter et al., 2010), reducing the pKAM without considering the pKFM does not guaranty a decrease in medial-compartment loading, as looked for in the treatment of medial knee OA (Reeves and Bowling, 2011). Indeed, if an intervention increases the pKFM while it reduces the pKAM, it could result in an increase in medial-compartment loading (Walter et al., 2010). Today, the exact relationship between changes in pKAM, pKFM and medial-compartment loading is unknown. Therefore, a conservative reading of the literature suggests that gait interventions for medial knee OA should reduce the pKAM by 10% or more without increasing the pKFM. Yet, it is unknown if this more specific change, referred here as *dual kinetic change*, is feasible through gait retraining because prior studies focused on pKAM reductions. In fact, as shown in Table 1, previous studies that analyzed the pKFM either reported no statistically significant changes or reported pKFM increases. Since these studies analyzed the change at the group level, the absence of significant change indicates that the changes differed among participants, with a portion of them increasing the pKFM. Consequently, it is clear that gait modifications used to reduce the pKAM could increase the pKFM, and there is a need to determine the feasibility of achieving the dual kinetic change to help the design of future gait retraining protocols.

Modifications in foot progression angle (FPA) and step width (SW) have been shown to change the pKAM (Favre et al., 2016) and have been frequently used in gait retraining for medial knee OA (Table 1). Surprisingly, modifying stride length (SL) received much less attention, although this could change knee kinetics (Russell et al., 2010) and is regularly used in other applications, such as prevention of running injury (Schubert et al., 2014). Since prior medial knee OA gait retraining studies have shown that the responses to gait modifications are subject-specific (Favre et al., 2016, Uhlrich et al., 2018), it could be extremely valuable to have the possibility to modify a third variable (SL) in addition to FPA and SW, especially when targeting more specific change, like the dual kinetic change. Furthermore, a gait retraining system using augmented-reality was recently introduced to facilitate simultaneous modifications in FPA, SW and SL (Bennour et al., 2018), meaning that it could be possible to optimize knee OA rehabilitation by combining these modifications (Shull et al., 2011; Favre et al., 2016). It is important that gait retraining maintains normal walking speed for everyday quality of life and long-term general heath. Therefore, it is understood that SL modifications go along with inverse modifications in cadence (Grieve and Gear, 1966).

The primary objective of this study was to characterize the feasibility of achieving the dual kinetic change individually through modifications in footprint parameters. This study also aimed at evaluating the added value of modifying SL while maintaining normal walking speed. Healthy participants were tested in this preliminary work involving the recording of many gait trials, to avoid pain or fatigue. It was hypothesized that participants could achieve the dual kinetic change of a pKAM reduction of 10% or more without pKFM increase and that, for some participants, the dual kinetic change would be achievable with SL modifications. No hypothesis was formulated regarding the directionality of FPA, SW and SL modifications necessary to reach the dual kinetic change because prior literature showed the modifications to be participant-specific (Favre et al., 2016; Jackson et al., 2018; Uhlrich et al., 2018).

2. Method

2.1. Participants

Eleven healthy subjects (7 males), without history of lower-limbs surgery, knee pain or locomotion difficulty, participated in this IRB-approved study after providing informed consent. Participants were of mean (±standard deviation) age, height and weight of 24.9 ± 2.5 years old, 1.82 ± 0.08 m and 68.7 ± 9.3 kg, respectively. Since the study objectives were of descriptive nature, the sample size was defined based on prior gait modification studies with comparable objectives (Cheung et al., 2018; Favre et al., 2016; Jackson et al., 2018; Shull et al., 2013b).

2.2. Experimental procedure

The participants were equipped with reflective markers and performed multiple gait trials with their own casual shoes on a 10 m long instrumented walkway (Bennour et al., 2018). A motion capture system (Vicon, Oxford, UK) and floor-embedded force-plates (Kistler, Winterthur, CH) were used to measure the kinetics of the right knee (pKAM and pKFM) and the spatio-temporal parameters (FPA, SW, SL and walking speed) during one cycle in the middle of the trials following common methods (Bennour et al., 2018; Favre et al., 2009; Zabala et al., 2013). In addition, two projectors were used to display instruction footprints on the floor that could be modified in terms of FPA, SW and SL (Fig. 1) (Bennour et al., 2018).

Gait was recorded in two phases. During the first phase, five trials at self-selected normal walking speed were collected. No footprint instructions were provided to the participants at this point. The five trials were then analyzed to determine the normal FPA, SW, SL and walking speed of the participants. Next, instruction footprints corresponding to the normal FPA, SW and SL of the participants were displayed on the floor and time was given to the participants to practice walking on the projected footprints (Edd et al., 2020). To help the participants stepping following the instruction footprints, each time a trial was completed during the practice period, the foot placements of the participants were displayed on top of the instruction footprints (Bennour et al., 2018). The participants needed about 5 min and 10 trials to get used to walking on the projected footprints. The second phase of gait recording started after the participants felt confident walking on footprint instructions. During this phase, the participants were asked to walk on modified footprint instructions. Twelve modifications with respect to normal gait were recorded in the following order for all the participants: −20, −13, −6 and +10° in FPA; +0.20, +0.13, +0.06 and −0.10 m m in SW; and −0.20, −0.13, −0.06 and +0.10 m in SL. These modifications were defined based

Table 1
Overview of prior biofeedback gait retraining studies for knee osteoarthritis (OA).

Study	Overall retraining objectives	Strategy	Feedback	Experiment		Results	
				Population	Observation period	Change in (1st) peak KAM*	Change in peak KFM*
Barrios et al. (2010)	KAM decrease	Indirect - decrease FPKA	FPKA displayed on a screen	8 AP	Immediate	**−20% (p = 0.027)**	N/R
					1 month follow-up	**−20% (p = 0.019)**	N/R
Dowling et al. (2010)	KAM decrease	Indirect - medial weight transfer at the foot	Vibration at the shoe based on plantar pressure	9 AP	Immediate	**−14% (p < 0.01)**	N/R
Hunt et al. (2011)	KAM decrease	Indirect - TL of 4°	TL displayed on a screen	9 AP	Immediate	−7% (p-value not reported)	N/R
		Indirect - TL of 8°				**−21% (p < 0.05)**	N/R
		Indirect - TL of 12°				**−25% (p < 0.05)**	N/R
Shull et al. (2011)	>30% KAM decrease	Indirect - modify FPA, TS and TA	Vibration at the back, knee and foot based on TS, TA and FPA	9 AP	Immediate	**−1.5 %BW*Ht (p < 0.001)**	N/R
Wheeler et al. (2011)	KAM decrease	Direct - decrease KAM	KAM displayed on a screen	16 AP	Immediate	**−20% (p < 0.001)**	N/R
			Vibration at the arm based on KAM			**−21% (p < 0.001)**	N/R
Shull et al. (2013a)	KAM decrease, without KFM increase	Indirect - decrease FPA	Vibration at the arm based on TA	12 KOAP	Immediate	**−13% (p < 0.01)**	−0.03 % BW*Ht (p = 0.85)
Shull et al. (2013b)	10% KAM decrease	Indirect - decrease FPA and/or increase TS	Vibration at the arm and back based on TA and TS	10 KOAP	Post-training (6 weeks)	**−0.5 %BW*Ht (p < 0.01)**	−0.28 % BW*Ht (p = 0.35)
					1 month follow-up	**−0.44 %BW*Ht (p < 0.05)**	−0.52 % BW*Ht (p = 0.08)
Hunt and Takacs (2014)	KAM decrease	Indirect - increase FPA	FPA displayed on a screen	15 KOAP	Post-training (10 weeks)	−0.26 %BW*Ht (p = 0.12)	+0.13 % BW*Ht (p = 0.67)
Ferrigno et al. (2015)	KAM decrease, without KFM increase	Indirect - medial weight transfer at the foot	Sound based on plantar pressure	22 AP	Immediate	**−15% (p < 0.001)**	−0.20 % BW*Ht (p = 0.34)
Van den Noort et al. (2015)	KAM decrease	Direct - decrease KAM	KAM displayed on a screen (diverse visual feedbacks)	12 AP	Immediate	**Between −56% and −45% (all p ≤ 0.01)**	N/R
		Indirect - increase HIR	HIR displayed on a screen (diverse visual feedbacks)			Between −5% and −19% (all p ≥ 0.19)	N/R
Erhart-Hledik et al. (2017)	KAM decrease	Indirect - medial weight transfer at the foot	Vibration at the shoe based on plantar pressure	10 KOAP	Immediate	**−6% (p = 0.04)**	+0.03% BW*Ht (p = 0.90)
Charlton et al. (2019)	KAM change	Indirect - FPA of −10°	FPA displayed on a screen	15 KOAP	Immediate	−0.08 Nm/kg (no statistics for comparison with natural walking)	N/R
		Indirect - FPA of 0°				−0.04 Nm/kg (no statistics for comparison with natural walking)	N/R
		Indirect - FPA of 10°				+0.00 Nm/kg (no statistics for comparison with natural walking)	N/R
		Indirect - FPA of 20°				+0.03 Nm/kg (no statistics for comparison with natural walking)	N/R
Cheung et al. (2018)	greater than20% KAM decrease	Direct - decrease KAM	KAM displayed on a screen	10 KOAP	Post-training (6 weeks)	**−22% (p < 0.001)**	N/S (p-value not reported)
					6 months follow-up	**−25% (p = 0.01)**	N/S (p-value not reported)
Jackson et al. (2018)	greater than20% KAM decrease	Direct - decrease KAM	KAM displayed on a screen	11 AP	Immediate with feedback	**−23% (p = 0.007)**	+33% (p-value not reported)
					Immediate without feedback	**−21% (p = 0.009)**	+25% (p-value not reported)
					5 min after immediate	**−24% (p = 0.008)**	**+35% (p = 0.04)**
Richards et al. (2018a)	10% KAM decrease, with limited KFM increase	Direct - decrease KAM	KAM displayed on a screen	16 KOAP	Post-training (6 weeks)	**−0.22 %BW*Ht (p = 0.05)**	+0.11 % BW*Ht (p = 0.53)
					3 months follow-up	−0.31 %BW*Ht (p = 0.18)	+0.02 % BW*Ht (p = 1.00)
					6 months follow-up	−0.21 %BW*Ht (p = 0.26)	+0.20 % BW*Ht

(continued on next page)

Table 1 (*continued*)

Study	Overall retraining objectives	Strategy	Feedback	Experiment: Population	Experiment: Observation period	Results: Change in (1st) peak KAM*	Results: Change in peak KFM*
							(p = 0.24)
Richards et al. (2018b)	10% KAM decrease	Direct - decrease KAM	KAM displayed on a screen (version 1)	40 KOAP	Immediate	−0.10 %BW*Ht (p = 0.15)	−0.02 % BW*Ht (p = 1.00)
			KAM displayed on a screen (version 2)			**−14% (p < 0.001)**	**+22% (p = 0.005)**
			Sound based on KAM			−0.11 %BW*Ht (p = 0.06)	+0.01 % BW*Ht (p = 1.00)
Uhlrich et al. (2018)	KAM decrease	Indirect - modity FPA	Vibration at the tibia based on FPA	20 AP	Immediate	**−19% (p-value not reported)**	**+12% (p = 0.023)**

The studies summarized in this table were selected based on the inclusion/exclusion criterion of two recent systematic literature reviews on knee OA gait retraining (Bowd et al., 2019; Richards et al., 2017).

Abbreviations: KAM = knee adduction moment; KFM = knee flexion moment; HIR = hip internal rotation; FPKA = frontal plane knee angle; FPA = foot progression angle; TS = trunk sway; TL = trunk lean; TA = tibia angle; AP = asymptomatic participant; KOAP = knee osteoarthritic patient; N/R = not reported; N/S = average change not reported, but change indicated as statistically non-significant.

*Average change of the study population (group level).

Bold: change statistically significant.

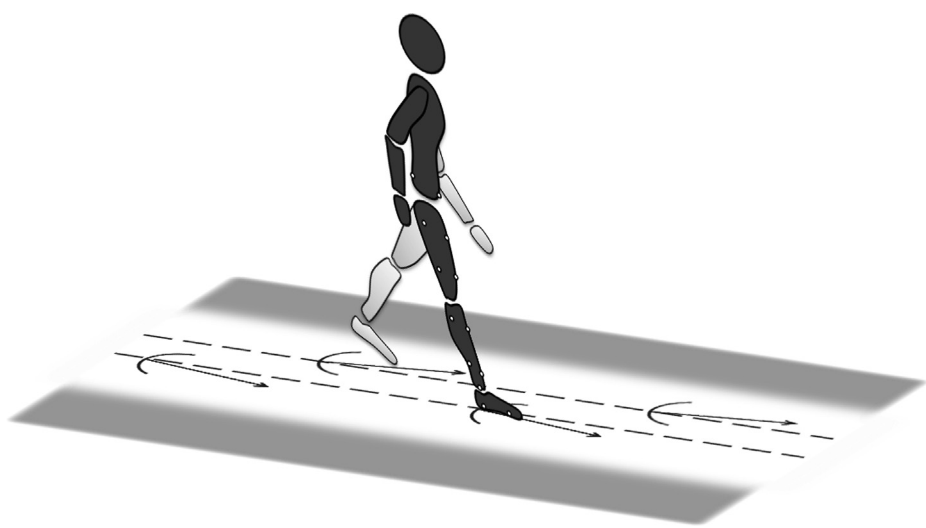

Fig. 1. Illustration of the experimental setup with a participant walking on ground-projected instruction footprints.

on pilot data and prior publications to span the modifications susceptible to trigger pKAM reductions of 10% or more without causing discomfort (Bennour et al., 2018; Cheung et al., 2018; Favre et al., 2016; Richards et al., 2018a). The modifications were applied to both, left and right, footprints. The participants could practice each modification as many times as they wanted, before the recording of three trials. When the participants were unsatisfied with a trial, it was recorded again. The participants were asked to maintain their normal walking speed during the trials with modifications, and trials with speed differing from the normal speed by more than 10% were repeated. After each modification, a single-answer multiple choice question was asked to the participants to classify the modification as either “I could walk like this in everyday living” or “I am not willing nor able to walk like this in everyday living”.

2.3. Statistical analysis

For each participant, the pKAM and pKFM measures were averaged per walking condition (normal and 12 modifications) and these average values were used to calculate the relative changes induced by the modifications with respect to the normal condition. Then, for each participant and each modification, it was determined if the dual kinetic change of pKAM reduction by 10% or more without pKFM increase was achieved and descriptive statistics was used to report these results. Additionally, bilateral Wilcoxon signed rank tests were performed to determine if the overall change in pKAM for the group of participants was different from a decrease of 10%. Similar tests were done to determine if the changes in pKFM differed from zero. Significance level was set *a priori* at 5% for these tests. Data processing and statistical analyses were done with MATLAB version R2018b (MathWorks, Natick, MA).

3. Results

When walking normally (without instructions), the participants walked at a median {interquartile range; IQR} speed of 1.55 {0.20} m/s, with FPA of 4.7 {5.3}°, SW of 0.10 {0.02} m and SL of 1.62 {0.14} m. The average ± standard deviation differences between instructions and actual footprints during the 396 trials recorded with modifications were −0.3 ± 3.2° for FPA, 0.001 ± 0.023 m for SW, and 0.007 ± 0.019 m for SL.

Individual analyses showed that the 11 participants could reduce their pKAM by 10% or more without increasing their pKFM with the modifications tested in this study (Table 2). For nine of them, this dual kinetic change could be achieved with modifications classified as possible in everyday living. Modifications leading to the dual kinetic change varied among participants. In fact, with the modifications participants could adopt in everyday living, the dual kinetic change could be achieved for seven participants by modifying FPA (#2, #3, #5, #6, #7, #9 and #11) or SL (#1, #2, #6, #7, #9, #10 and #11) and for three participants by modifying SW (#1, #2 and #10). The averaged KAM and KFM curves of the participants achieving the dual kinetic change are presented separately for each modification in Fig. 2.

When looking at the results from the participant stand points, one participant (#2) could achieve the dual kinetic change by modifications in any of the three footprint parameters, six participants (#1, #6,#3, #9, #10 and #11) could achieve it by modifications in one or two footprint parameters, and two participants (#3 and #6) could achieve it only with FPA modifications (Fig. 3).

Among the seven participants who achieved the dual kinetic change with FPA modifications classified as possible in everyday living, the smallest absolute amplitudes of modification were toeing-in by 6° for three participants and toeing-in by 12° for the remaining four participants (Table 2). These modifications resulted in a median {IQR} pKAM reduction of 19.4 {10.1}% and a median pKFM reduction of 16.1 {7.4}% (Table 3).

Regarding the three participants achieving the dual kinetic change with modifications in SW classified as possible in everyday living, the smallest absolute amplitudes of modification were SW narrowing by 0.1 m for two participants and SW widening by 0.06 m for the remaining participant (Table 2). These modifications induced in median pKAM and pKFM reductions of 12.0 {1.4}% and 23.5 {17.2}% (Table 3).

For the seven participants who achieved the dual kinetic change with SL modifications classified as possible in everyday living, the smallest absolutes amplitudes of modification were SL shortening by 0.06 m for two participants, SL shortening by 0.13 m for four participants, and SL shortening by 0.2 m for the remaining participant (Table 2). These modifications resulted in median pKAM and pKFM reductions of 16.3 {4.2}% and 9.3 {21.7}% (Table 3).

Analyzing the kinetic changes of the group of participants indicated that seven of the 12 modifications (FPA-6, SW-0.1, SW+0.06, SW+0.13, SL-0.2, SL-0.13 and SL-0.06) induced changes in pKAM not statistically significantly different from a reduction of 10% and two modifications (FPA-20 and FPA-13) reduced the pKAM by more than 10% (Fig. 4, upper graph). None of these nine modifications induced a significant group increase in pKFM, with two of them (FPA-13 and SW-0.1) even reducing the pKFM (Fig. 4, lower graph).

4. Discussion

This study showed that the dual kinetic change, consisting in reducing the pKAM by 10% or more without increasing the pKFM, is individually feasible through modifications in footprint parameters. This result is important because it suggests that gait retraining for medial knee OA could aim for more specific kinetic changes than simply pKAM reduction, as it has been the case so far. This result reveals even more important when we consider that medial knee OA literature recommends no pKFM increase (Manal et al., 2015: Walter et al., 2010) and that prior gait retraining studies clearly indicate that the pKFM can increase if no enough attention is paid to it (Table 1). Consequently, since the dual kinetic change is feasible, future gait retraining intervention for medial knee OA should probably target a reduction in pKAM without increase in pKFM for each participant.

The second hypothesis was also supported, with seven out of the 11 participants being able to achieve the dual kinetic change through SL modifications. This result is also substantial, as SL modifications were as effective as FPA modifications and twice as effective as SW modifications, when considering the modifications classified as suitable for everyday living. Although comparing modification variables is tricky because testing modifications of other amplitudes could have changed the results, the value of considering SL modifications in medial knee OA gait retraining appears undeniable both for their capacity to change knee kinetics and their acceptability potential. The dual kinetic change was always achieved by shortening SL. Since walking speed was maintained during the experiment, these SL modifications could also be seen as cadence increases (Grieve & Gear, 1966). This relationship could reveal very useful in the future, particularly for routine rehabilitation, as cadence modifications could be easy to initiate (Nijs et al., 2020) and wearable devices already exist to measure walking speed and cadence (Fasel et al., 2017). Moreover, it is worth mentioning that, while modifying SL is novel in knee OA gait retraining, SL modifications have already been considered

Table 2
Feasibility of reducing the peak knee adduction moment (pKAM) by 10% or more, without increasing the peak knee flexion moment (pKFM).

Participant	Foot progression angle modification, °				Step width modification, m				Stride length modification, m			
	−20	−13	−6	10	−0.10	+0.06	+0.13	+0.20	−0.20	−0.13	−0.06	+0.10
1					**x**				x	**x**		
2	(x)	x	**x**		**x**				x	**x**		
3		**x**										
4	(x)											
5			**x**	x								
6	(x)	**x**							**x**			
7	x	x	**x**						x	x	**x**	
8	(x)	(x)										
9		**x**							x	**x**		
10					(x)	**x**			x	**x**		
11	(x)	**x**									**x**	x
Number of participants achieving the dual change	1(5)	6(1)	3	1	2(1)	1	0	0	6	5	2	1

Modifications achieving the dual kinetic change are marked by an "x". For sake of clarity, modifications not achieving the dual kinetic change are let blank. Marks into brackets, "(x)", indicate modifications that the participants classified as "not be willing or able to adopt in everyday living". For each modification variable, the smallest absolute amplitude of modification achieving the dual kinetic change and classified as possible in everyday living is marked in bold, "**x**". The actual pKAM and pKFM changes for the gait modifications in bold are reported in Table 3.

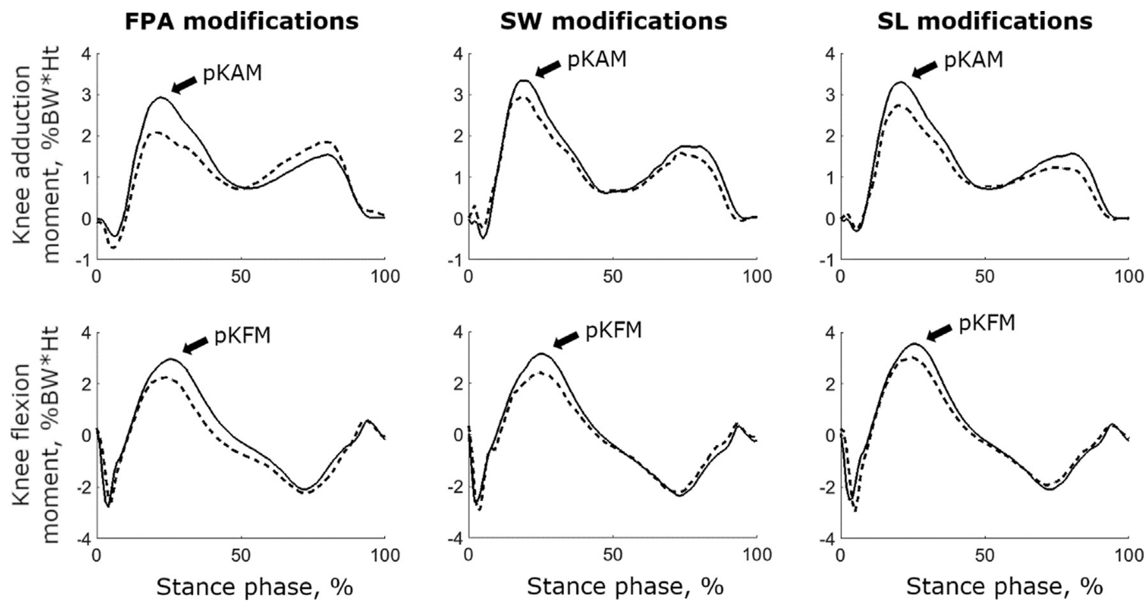

Fig. 2. Average knee adduction moment (KAM, top) and knee flexion moment (KFM, bottom) for the participants achieving the dual kinetic change with modifications in foot progression angle (FPA, left), step width (SW, middle), and stride length (SL, right). Continuous lines correspond to the normal walking trials (without modification), and dash lines to the walking trials with the modifications of interest. The arrows indicates the peaks of interest (pKAM and pKFM).

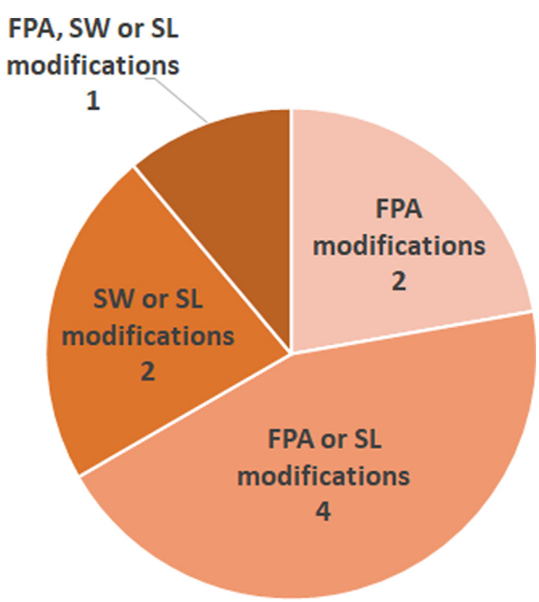

Fig. 3. Distribution, among participants, of the footprint modifications that allowed achieving the dual kinetic change while being classified as possible in everyday living. The number in each slice corresponds to the number of participants who achieved the dual kinetic change with modifications in foot progression angle (FPA), step width (SW) and/or stride length (SL).

for other applications, such as running injuries (Schubert et al., 2014).

The footprint modifications to achieve the dual kinetic change differed among participants. This observation well agrees with prior research that already reported participant-specific changes in knee kinetics in response to footprint modifications (Favre et al., 2016; Uhlrich et al., 2018). Therefore, widening the range of modifications that could be used for medial knee OA by acting on SL, in addition to FPA and SW, could be valuable. In the present study, FPA, SW and SL were modified in isolation. However, in the future, combining them could improve the retraining procedure. For example, instead of modifying one or another parameter by a large amplitude, it could be interesting to modify two or three parameters by smaller amplitudes (Shull et al., 2011). In addition to personalizing the intervention, further research will also be necessary to improve our understanding of the variability among individuals. For instance, a recent study on a footwear intervention for knee OA reported an association between the natural FPA and the KAM changes in response to the intervention (Ulrich et al., 2020).

Another originality of this study is the use of augmented-reality to help the participants modifying their footprint parameters in the framework of knee OA gait retraining. Previously, gait retraining systems for knee OA based on footprint modifications have all been designed using biofeedback, either visual, haptic or auditory (Table 1). With the biofeedback approach, the modifications are not demonstrated to the participants; participants have to modify their walking patterns based on signals dissociated from their physical meaning. While biofeedback could be beneficial during the learning process taking place once the modifications for a given individual have been identified (Richards et al., 2018c), this approach could complicate the identification of the individual modifications necessary to induce the biomechanical changes because concurrent modifications in FPA, SW and SL could be tedious to achieve with biofeedback (Chen et al., 2017). The augmented-reality approach used in the present study is therefore promising for knee OA gait retraining because FPA, SW and SL modifications can be demonstrated and easily achieved by the participants. Gait retraining for knee OA is still at an early stage and further works will be necessary to improve the systems and protocols, as well as determining which strategies are best for which patients.

The present data also highlight the ambiguity that group statistics can generate when reporting biomechanical changes after gait retraining. For example, as a group of participants, the modification consisting in decreasing the FPA by 13° statistically significantly reduced the pKAM by more than 10% and statistically significantly reduced the pKFM. This modification therefore appears as plainly achieving the dual kinetic change. However, only seven participants (64% of the study population) actually achieved the dual kinetic change with this modification. The other participants either did not achieve 10% pKAM decrease (one participant) or had pKFM increases (three participants). This ambiguity between the changes

Table 3
Changes in peak knee adduction moment (pKAM) and peak knee flexion moment (pKFM) for the smallest absolute amplitude of modification achieving the dual kinetic change and classified as possible in everyday living (modifications in bold in Table 2).

Participant	Foot progression angle modification		Step width modification		Stride length modification	
	pKAM	pKFM	pKAM	pKFM	pKAM	pKFM
1			−12.0	−1.0	−15.2	−16.9
2	−15.7	−29.2	−10.5	−35.4	−17.8	−32.7
3	−17.8	−12.4				
4						
5	−19.4	−12.9				
6	−42.7	−15.2			−23.6	−2.1
7	−13.9	−24.2			−17.9	−0.4
8						
9	−25.2	−18.5			−12.1	−33.3
10			−13.4	−23.5	−11.2	−4.1
11	−28.4	−16.1			−16.3	−9.3
Median {IQR} changes	−19.4 {10.1}	−16.1 {7.4}	−12.0 {1.4}	−23.5 {17.2}	−16.3 {4.2}	−9.3 {21.7}

Changes are reported in percent of the values measured during the normal walking condition. The median and interquartile range {IQR} changes of the participants achieving the dual change are reported at the bottom of the table. Blank cells indicate modifications that did not achieve the dual kinetic change in a manner classified as possible in everyday living, whatever their amplitudes, for the given participant.

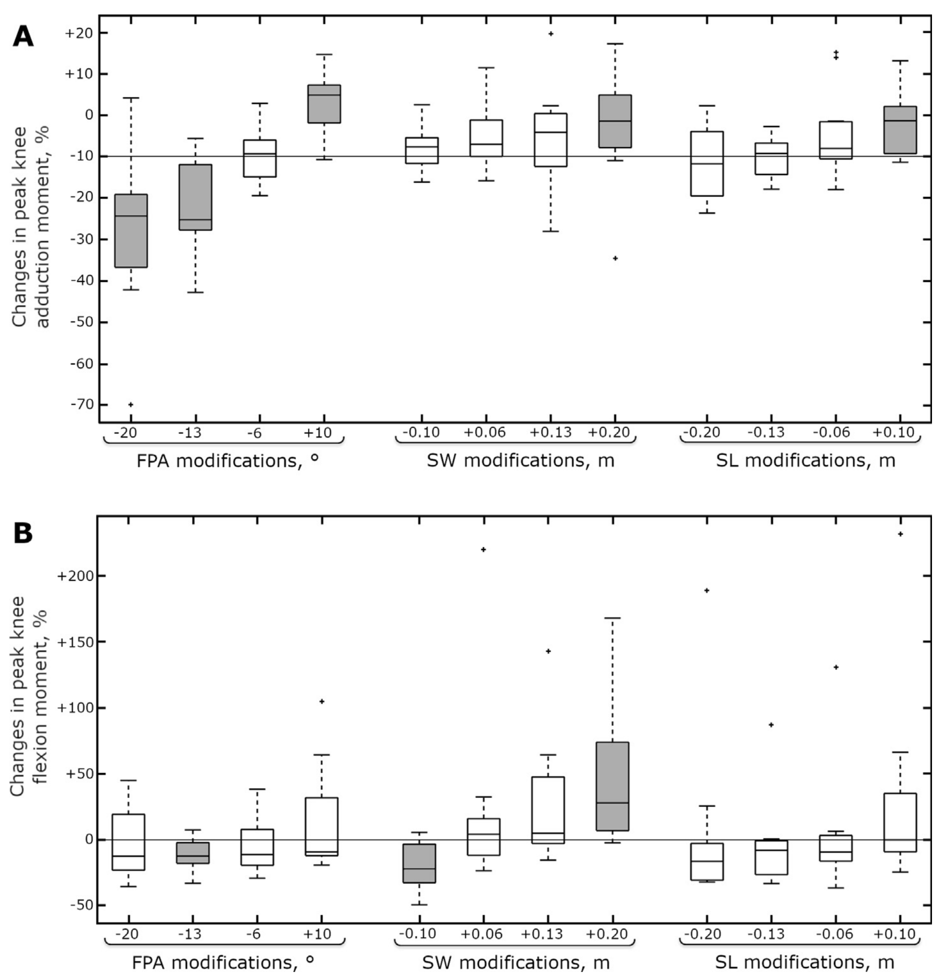

Fig. 4. Boxplots of the changes in (A) peak knee adduction moment (pKAM) and (B) peak knee flexion moment (pKFM) induced by foot progression angle (FPA), step width (SW) or stride length (SL) modifications. Changes are expressed in percent of the values measured during the normal walking condition. Shaded boxplots represent modifications inducing changes significantly different (smaller or larger) from −10% in pKAM or from 0% in pKFM ($p < 0.05$).

as a group and as individuals could be prejudicial when interpreting the clinical improvements after a gait retraining program because, as with the present example, reporting that the targeted biomechanical changes was achieved for the group does not mean that every participant individually achieved the target. In consequence, future gait retraining studies are encouraged to report the percentage of participants reaching the target and, when appropriate, to analyze separately the subgroup of participants that achieved the target and the subgroup that did not.

This study has some limitations that should be discussed. First, while it is extremely encouraging that the 11 participants could achieve the dual kinetic change with at least one of the modifications, this result should not be over interpreted as: “every individual can achieve the dual kinetic change”. The present study aimed to test a limited number of individuals with a limited number of predefined modifications to characterize the feasibility of the dual kinetic change. Now, that the feasibility has been demonstrated, further studies with larger sample size and personalized footprint modifications will be necessary to define the percentage, and maybe the profile, of the individuals capable of achieving and maintaining the dual kinetic change. For example, it is interesting to note that, while all the participants achieved the dual kinetic change, about a fifth said that they would not be willing nor able to walk with the modification(s) inducing this change in everyday living. Again, although instructive, this percentage should be interpreted with caution as testing other modifications or other individuals could have led to a different percentage.

Although the dual kinetic change was selected conservatively based on prior literature (Butler et al., 2007; Walter et al., 2010; Shull et al., 2013b; Manal et al., 2015; Richards et al., 2018a), it constitutes a second limitation, as no clear target for pKAM and pKFM changes has yet been defined for medial knee OA. Nevertheless, adjusting the pKAM and pKFM targets would not modify the main findings of this study. Asymptomatic participants were tested to facilitate the recording of numerous trials without pain or fatigue. This constitutes another limitation, and future studies are therefore necessary to confirm the results in patients with medial knee OA. Finally, longitudinal studies will also be needed to evaluate the effects learning and long-term practice of the footprint modifications could have on knee kinetics.

In conclusion, this study demonstrated the feasibility of reducing the pKAM by 10% or more without increasing the pKFM individually through modifications in footprint parameters. This suggests that more specific changes than simply pKAM reductions can be targeted in footprint-based gait retraining. The results also confirmed the need for subject-specific retraining approaches, where the footprint parameter modifications are defined individually for each patient. Additionally, the study showed that the dual kinetic change could be achieved with SL modifications, therefore widening the range of modifications that could be used for gait retraining of medial knee OA. Finally, this work introduced a new, augmented-reality, approach to help the modification of footprint parameters in the framework of knee OA rehabilitation.

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Declaration of Competing Interest

The Authors confirm that none of the Authors has any conflict of interest regarding the work presented in this manuscript and that the sources of founding, which had no influence on this research, are cited properly in the manuscript.

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