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Full length article

The learning process of gait retraining using real-time feedback in patients with medial knee osteoarthritis

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ABSTRACT

The objective of this study was to investigate the learning process of knee osteoarthritis (KOA) patients learning to change their foot progression angle (FPA) over a six-week toe-in gait training program.

Sixteen patients with medial KOA completed a six-week toe-in gait training program with real-time biofeedback. Patients walked on an instrumented treadmill while receiving real-time feedback on their foot progression angle (FPA) with reference to a target angle. The FPA difference (difference between target and actual FPA) was analyzed during i) natural walking, ii) walking with feedback, iii) walking without feedback and iv) walking with a dual-task at the start and end of the training program. Self-reported difficulty and abnormality and time spent walking and training were also analyzed.

The FPA difference during natural walking was significantly decreased from median 6.9 to median 3.6° i.e. by 3.3° in week six ($p < 0.001$); adding feedback reduced FPA difference to almost zero. However the dual-task condition increased the FPA difference at week one compared to the feedback condition (median difference: 1.8°, $p = 0.022$), but after training this effect was minimized (median difference: 0.6°, $p = 0.167$). Self-reported abnormality and difficulty decreased from median 5 to 3 and from median 6 to 3 on the NRS respectively ($p < 0.05$).

Patients with medial KOA could reduce the FPA difference during natural walking after the gait retraining program, with some evidence of a reduction in the cognitive demand needed to achieve this. Automation of adaptions might need support from more permanent feedback using wearable technologies.

1. Introduction

People with medial knee osteoarthritis (KOA) often have an increased knee adduction moment (KAM), which is associated with faster progression of the disease [1]. Modifying the foot progression angle (FPA) during gait can reduce the KAM [2–9]. Real-time biofeedback can be used to train gait modifications [3–5,8–10]. There is evidence that patients can learn to walk with gait modifications in the short-term (i.e. within session) and that the gait modifications have beneficial short-term biomechanical effects [2,5,8,9]. There is, however, limited evidence to show whether the modifications can truly be learnt. Similarly, the cognitive demand of walking with a modified gait pattern is unknown, although increases in cognitive demand are expected during the motor learning process [11]. Cognitive loading may be measured using functional near-infrared spectroscopy [12] or electroencephalography [13]. However, both techniques present problems relating to drift when measuring over a long period of time. Use of a concurrent dual-task offers a practical, alternative method of estimating the effect of cognitive demand during walking. Use of a dual-task paradigm has demonstrated the relationship between the cognitive and motor systems [14]. Deterioration of gait performance during walking with a dual-task condition suggests that gait is not completely automatic [15], despite locomotion control by the central pattern generator [16]. The dual-task paradigm represents the many important distractions during walking that are encountered daily, e.g. talking while walking.

In the absence of injury or illness, little conscious effort during normal walking is needed and the gait pattern is easily adapted to changes in the environment and/or terrain. Learning to modify the gait pattern is likely to interrupt the automaticity of normal locomotion and hence require increased cognitive demand. According to the Fitts and

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Posner three stage model of motor learning [11], we would expect that walking with a modified gait pattern would initially cause a steep increase in cognitive demand and that it would be performed with significant errors (1st stage of learning; cognitive phase). With increased practice time, we would expect increasing automaticity and reduced cognitive demand (2nd stage; associative phase) and with sufficient practice time we would expect the task to be performed with little or no cognitive demand (3rd stage; autonomous phase).

We can also consider changes in the motor-learning in terms of fast and slow learning. Fast learning is learning over a short period of time, typically learning within-session. That fast learning occurs during gait retraining has been demonstrated [2,8–10]. Slow learning occurs with repetitive practice over several training sessions with sufficient consolidation time, and leads to gradual, progressive improvements in performance [17]. Slow learning leads to changes in the representation of the learnt activity in the motor-cortex and long-term retention of the learnt skill [18].

The aim of this study was to evaluate the motor learning process during a six-week gait retraining program focused on toe-in gait in patients with medial KOA by assessing the difference in FPA between the target FPA modification and the actual FPA as the primary outcome. Specifically, we aimed to assess changes in the FPA difference as a result of a six-week gait training program during a) normal walking condition and b) a dual task condition, designed to challenge the patients. We hypothesized firstly, that the FPA difference would reduce after the training, indicating slow learning and an increase in automaticity, and secondly that introduction of a dual-task would increase the FPA differences.

2. Method

Sixteen patients with medial KOA (61.2 ± 5.8years, 12 female), completed a six week gait retraining program (one session per week) in the Virtual Reality lab at the VUmc. Patients were recruited from a previous study in this lab [9], with inclusion criteria being medial KOA, aged between 50 and 75, and at minimum a 10% reduction in the first peak KAM between normal walking and modified walking conditions in our previous study. Further inclusion and exclusion criteria are given in [9]. Ethical approval for this study was granted by the Medical Ethics Committee of the VU Medical Centrum, Amsterdam, Netherlands in September 2015. Patients provided written consent to participate in the study. Demographics of the included patients are presented in Table 1. Reflective markers positioned over the patient's lower limbs and trunk were used to calculate the FPA and KAM in real-time [19] during walking on an instrumented treadmill. Marker position data were recorded at 100 Hz, using a 10 camera Vicon motion-capture system. Ground reaction force data were recorded at 1000 Hz using two ForceLink force plates embedded in the treadmill [9]. Patients walked at self-selected comfortable walking speed.

Feedback on the participant's FPA was presented on a 180° screen in front of the treadmill, in the form of two arrows. Targets for FPA were determined based on a previous study [9], with a mean (SD) target angle across the group of 3.0 (2.5) degrees in-toeing. The targets were set specifically for each patient with a mean (SD) target change of 7.3° (4.5) towards in-toeing. Targets were presented as stationary arrows, which changed colour according to the FPA difference, Fig. 1.

Table 1
Characteristics of patients completing the training program.

	Mean (standard deviation)
Age	61.1 (5.7)
Gender	12F 4 M
Height	1.72 (0.08)
Weight	76.0 (12.2)
BMI	25.5 (2.9)
KL score	I: 10, II: 1, III: 4, IV: 1

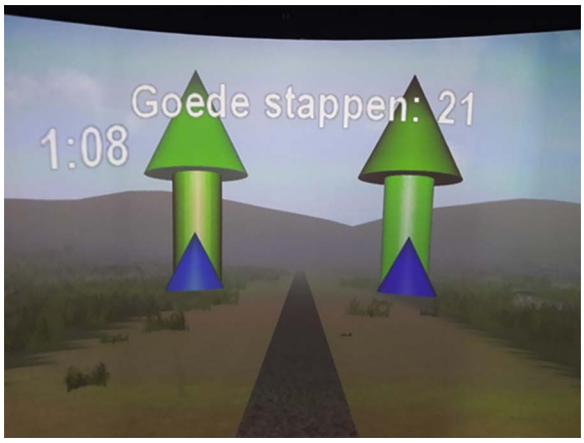

Fig. 1. Real-time feedback as seen by the patient while walking on the treadmill. The blue arrows represent the current position of the feet, with the larger arrows in the background representing the target angle. The difference between the actual and target angle is given by the colour of the large arrows (green is on target, orange is $\geq 2^{\circ}$ and $\leq 5^{\circ}$ either side of the target, red is $> 5^{\circ}$ either side of the target). The patient aims to align their actual foot progression arrow with the target arrow of the left and right foot separately resulting in green arrows when the actual and target angles are the same. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Faded feedback protocol used during the training program.

	Training time (min)	Feedback time (% of total time)
Week 1	9 (3 × 3 mins)	100
Week 2	12 (3 × 4 mins)	100
Week 3	15 (3 × 5 mins)	100
Week 4	18 (3 × 6 mins)	75
Week 5	21 (3 × 7 mins)	50
Week 6	12 (3 × 4 mins)	25

Training time increased from week 1 to week 5, while feedback time reduced after the third week, according to a faded feedback protocol [3,4,20], as shown in Table 2. This is considered to reduce reliance on feedback and improve retention of the learnt skill [21,22]. Due to additional measurements and time constraints, the total walking time in week six was reduced (unrelated to the faded feedback protocol).

During week one and week six we assessed the FPA difference during four conditions which were always performed in the same order: i) natural walking (no feedback), ii) walking with feedback on the FPA, iii) walking without feedback and iv) walking with a dual-task but without feedback on the FPA.

For the dual task, patients performed the Visual Stroop test [23] whilst walking on the treadmill. Words were displayed on the screen in front of the patient at 2 s intervals. For example if the word "green" appeared on the screen in a red font the response should be "Red". Patients were asked to maintain their modified FPA during the Stroop test, but were not told to prioritize either task.

Between sessions we asked participants to practice using the gait modification and to complete a weekly log book, to estimate a) time spent walking daily, b) time spent consciously using the modification daily (from 1 (not at all) to 4 (all of the time)), c) difficulty of walking with the modification (from 1 (no difficulty) to 10 (extreme difficulty)) and d) the abnormality of the modification (from 1 (completely normal) to 10 (completely abnormal)).

2.1. Data analysis

We post-processed the gait data using BodyMech (www.bodymech.nl), an in-house Matlab based biomechanics software used to calculate

joint and segment angles. We analyzed the FPA difference of both feet during four conditions, specifically i) **natural walking condition**, ii) **feedback condition**, iii) **retention condition** (no feedback) and iv) **dual-task condition** (visual Stroop test). From each complete gait cycle, we calculated the mean FPA across the stance phase and compared it to the target FPA to compute the difference in the FPA, as shown in Eq. (1).

$$FPA\ difference = Target\ FPA - Actual\ FPA \quad (1)$$

Furthermore we investigated the percentage of on-target steps achieved by each patient during each trial. We defined on-target steps as those where the FPA was ≤target angle + 2° (i.e. all steps that were on-target or less than 2° more externally rotated than the target).

Finally we investigated changes in the self-reported walking and training time and the self-reported difficulty and abnormality of the gait modification.

2.2. Statistical analysis

Prior to statistical analysis, all outcome measures were assessed for normality with Shapiro–Wilk and Kolmogorov-Smirnov tests. Firstly, we used Friedman's test (non-parametric repeated measure analysis of variance) to compare the FPA differences and percentage of on-target steps between the different conditions (n = 4) at the start and end of the gait training program. Post-hoc testing using the Wilcoxon signed rank test with correction for multiple tests was used to determine significant differences between the four conditions.

Secondly, we used the Wilcoxon signed rank test to assess differences in FPA difference and percentage of on-target steps between week one and week six within a specific condition.

Finally we used Friedman's test to assess changes in self-reported walking time, training time, abnormality and difficulty of walking with the modification across the training program. All analyses were performed using SPSS software, version 22.0 (SPSS, Chicago, IL, USA) and statistical significance was set to $\alpha = 0.05$.

3. Results

3.1. Accuracy of performance

Between week one and week six, the FPA difference reduced during all four conditions ($p < 0.001$); Table 3 and Fig. 2.

In week one, significant differences were noted between the FPA difference during **natural walking** and the other three conditions ($p < 0.001$) with lower FPA differences compared to the natural walking in all other conditions. Furthermore, the FPA difference during the **dual-task condition** was increased compared to the **feedback (single task) condition** ($p = 0.022$). In week six, the FPA difference during **natural walking** was again significantly higher than in the other conditions ($p < 0.01$), but no significant differences existed between the **dual-task condition** and the **feedback condition** ($p = 0.167$) or the **dual-task condition** and the **retention condition** ($p = 1.000$).

3.2. Consistency of performance

On a group level, consistency of performance improved between week one and week six with an increased percentage of on-target steps in all conditions in week 6 (Table 3). Consistency improved with **feedback** compared to the **natural walking condition** ($p < 0.001$) and remained higher during the **retention** and **dual-task** conditions. Significant differences were evidence between the **feedback** and **dual-task** conditions in both week one and week six ($p = 0.012$ and $p = 0.040$ respectively). High between-subject variability was observed in the trials, evidenced by high IQRs (Table 3).

Table 3
Error in foot progression angle and percentage of on-target steps (median, IQR) across four conditions and two time points.

	Natural walking (NW)		Feedback (FB)		Retention (R)		Dual Task (DT)		p value (across time)	p value (across conditions)	p value (post-hoc pairwise testing between week one and week six)	p value (post-hoc pairwise testing between conditions in week one[a])	p value (post-hoc pairwise testing between conditions in week six[a])
	Week 1	Week 6	Week 1	Week 6	Week 1	Week 6	Week 1	Week 6					
Difference in foot progression angle (°)	6.9 (4.7)	3.6 (3.7)*	0.7 (2.5)	0.1 (2.1)*	1.3 (4.5)	0.5 (2.6)*	2.5 (4.8)	0.7 (3.5)*	**< 0.001**	**< 0.001**	**NW, p < 0.001** **FB, p = 0.045** **R, p = 0.036** **DT, p = 0.030**	● **NW > FB, p < 0.001** ● **NW > R, p < 0.001** ● **NW > DT, p < 0.001** ● **FB = R, p = 1.000** ● **DT > FB, p = 0.022** ● **R = DT, p = 0.728**	● **NW > FB, p < 0.001** ● **NW > R, p < 0.001** ● **NW > DT, p = 0.008** ● FB = R, p = 1.000 ● FB = DT, p = 0.167 ● R = DT, p = 1.000
% of on-target steps	0.0 (7.9)	14.7 (45.4)*	68.5 (44.7)	90.8 (23.6)*	62.2 (78.8)	80.9 (43.4)*	36.6 (69.7)	77.8(83.7)*	**< 0.001**	**< 0.001**	**NW, p = 0.002** **FB, p = 0.009** **R, p = 0.034** **DT, p = 0.023**	● **NW < F, p < 0.001** ● **NW < R, p < 0.001** ● **NW < DT, p < 0.001** ● F = R, p = 0.283 ● **F > DT, p = 0.012** ● R = DT, p = 1.000	● **NW < F, p < 0.001** ● **NW < R, p < 0.001** ● NW = DT, p = 0.054 ● FB = R, p = 1.000 ● **FB < DT, p = 0.040** ● R = DT, p = 0.599

Significant differences between conditions (post-hoc testing) at $\alpha = 0.05$ shown in bold.
[a] With Bonferroni correction for multiple testing N.B. Positive FPA error represents a FPA that was more externally rotated than the target.
* Significant difference between week one and week six at $\alpha = 0.05$.

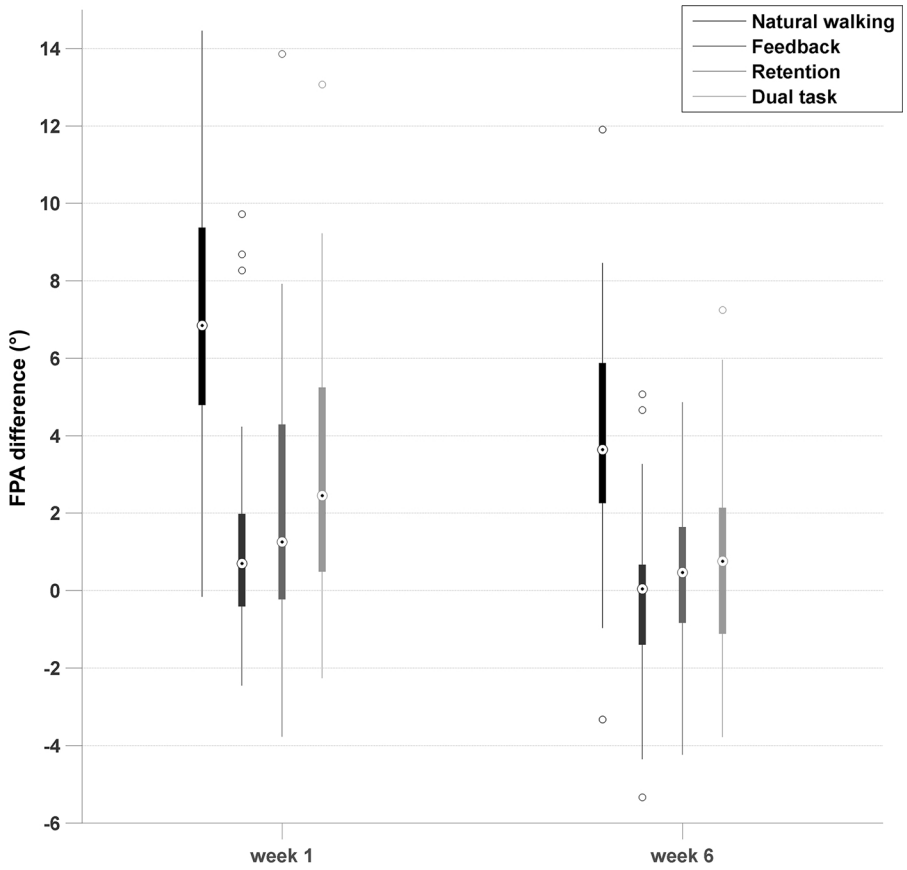

Fig. 2. Foot progression angle (FPA) difference in week 1 (start of training) and week 6 (end of training). A positive difference indicates that the FPA was more externally rotated compared to the target angle while a negative difference indicates that the FPA was more internally rotated compared to the target angle.

3.3. Self-reported outcome measures

Self-reported daily walking time did not change significantly during the training program, $p = 0.261$ (Fig. 3a). Of the total time spent walking, the self-reported training time, defined as the time spent walking with the modification, increased between week one and week five (from 3 to 4 on the NRS, $p = 0.023$) and week one and week 6 (from 3 to 4 on the NRS, $p = 0.005$) (Fig. 3b).

Difficulty of walking with the modification decreased during the training program ($p < 0.001$), with statistically significant changes noted between week one (median 5) and six (median 3, $p = 0.002$) and week two (median 5) and six (median 3, $p = 0.014$), as shown in Fig. 3c. The abnormality of walking decreased significantly during the training program with statistically significant reductions between week one (median 6) and six (median 3, $p < 0.001$), week two (median 6) and six (median 3, $p = 0.002$) and week one (median 6) and five (median 3.5, $p = 0.006$), (Fig. 3d).

4. Discussion

In this study we explored the learning process during toe-in gait retraining of patients with medial knee OA over a six-week gait training program. We analyzed firstly, accuracy of performance, expressed by the FPA difference and secondly, consistency of performance, expressed by the percentage of on-target steps, under four conditions (natural walking, feedback, retention and dual-task conditions). Both accuracy and consistency of performance improved over the training period with large reductions in the FPA difference and an increased percentage of on-target steps observed in all conditions. This suggests that medial KOA patients not only are able adapt their gait pattern within-session, but also to learn and adopt the gait modifications over several sessions. Despite these improvements, during natural walking in week six, the FPA difference and the percentage of steps on-target indicated that, for some patients, it was still difficult to achieve the target gait modification while for others it was more autonomous, as evidenced by a median FPA difference of 3.6° (IQR 3.7°) and median 14.7% on-target steps with a high IQR, 45.4%.

Previous studies investigating gait modifications in KOA have focused on reporting changes in KAM under standardized laboratory conditions [2–6,24,25] and most trained the gait modifications within a single session (and single-task conditions) only. These studies provide evidence of fast-learning but not of slow-learning, required for longer-term retention of the learnt gait pattern. Studies over longer training periods (several weeks) have shown mixed results regarding retention of the learnt gait pattern. Barrios, Crossley [20] trained eight healthy subjects with varus malalignment to walk with reduced knee varus but reported no change post-training. This is in contrast to the changes in FPA in our results and suggests that slow learning did not occur in the participants in [20]. Hunt and Takacs [4] reported that during a ten-week toe-out gait intervention, patients walked with an average FPA difference of 2.6° during training sessions. Post-training the average change in self-selected FPA was 6.7°. Patients were encouraged to change their FPA by 10°, but individual data shows that only 5/15 patients achieved this target [4]. These results together suggest that, while within-session fast learning means that short-term modifications in the gait pattern appear to be easily achievable [2,6,9,10], it is more difficult to maintain the modifications over a longer period. This suggests limited slow-learning.

The patient's own perception of difficulty and abnormality of using the modifications may influence the ability to learn the modifications. Our results show decreases in self-perceived abnormality and difficulty over the training program, similar to Refs. [4] and [20]. Reduced

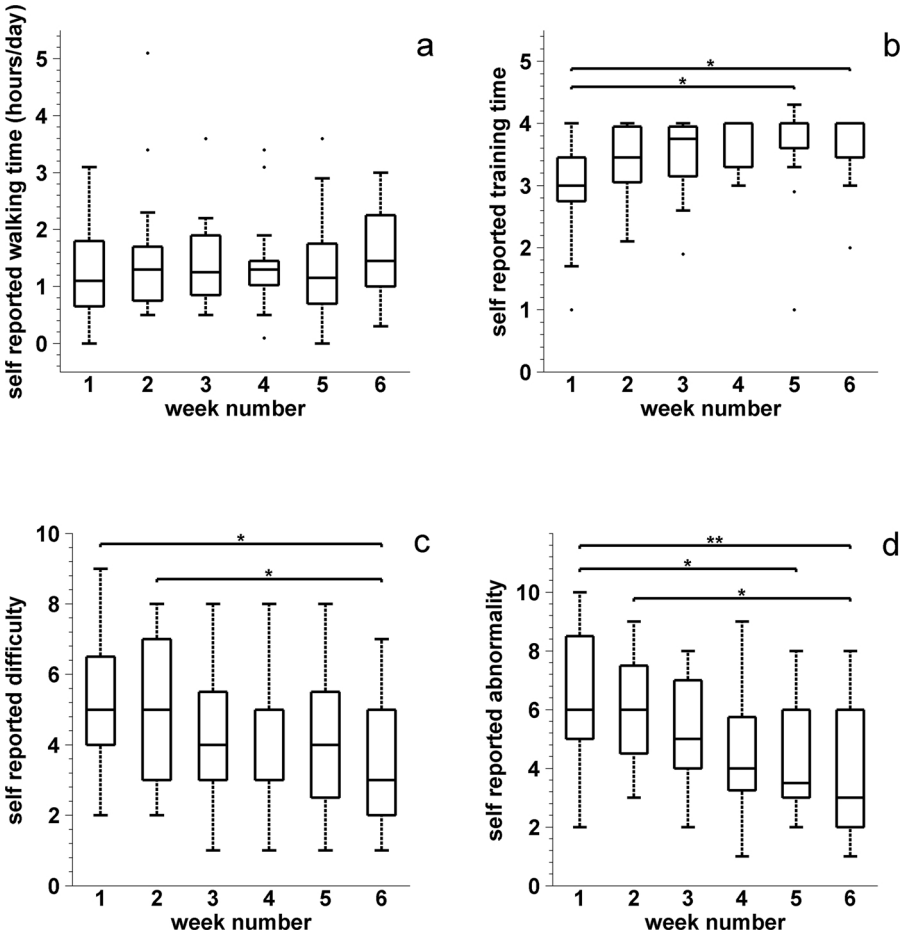

Fig. 3. Self-reported time spent walking daily (a), time spent training time (time spent walking with the modification) (b), self-reported difficulty on a scale of 1–10 where 1 represents no difficulty and 10 represents extreme difficulty (c) and self-reported abnormality on a scale of 1 to 10 where 1 represents completely normal and 10 completely abnormal (d) of walking with the gait modification. The time spent walking with the modification was assessed on a four point scale, where 1 represents not at all and 4 all of the time. * significant difference at $\alpha = 0.05$ and ** significant difference at $\alpha < 0.001$.

difficulty may facilitate the motor learning process and allow the gait modification to be performed more automatically. According to the Fitts and Posner model of motor learning [11] the cognitive demand of a given motor task decreases with time/practice as the skill becomes more automatic. This reduction in cognitive loading and difficulty could be important for transferring the learnt skill from the laboratory to the real-world environment.

In this study, between-session changes in the FPA were generally lower than the between-condition changes. This can be explained by considering that fast learning is generally associated with large improvements compared to smaller, incremental improvements during slow learning. For sustainable and long-term effects, slow learning, involving mechanisms of neuronal organization, is likely required [17].

Considering the three stages of learning proposed by Fitts and Posner [11], we suggest that post-training, patients were in the 2nd stage, the associative stage where the task was performed with improved consistency and less cognitive demand, but was not completely automatic. Reaching the 3rd stage of learning (autonomous stage) of the gait pattern seems necessary in order for the gait modifications to be clinically useful. To achieve this, practice hours should increase, for which small and wearable sensors that can be used for training in the home environment may be needed. Recent developments in this field include devices to discretely measure the FPA [27] or to estimate the KAM [28–31]. Furthermore, real-time feedback to the patient via a simple and discrete device may facilitate faster motor learning.

In this study, we used a dual-task paradigm to investigate the additional cognitive demand of walking with toe-in gait in people with medial KOA. Previous research in healthy controls showed that self-perceived cognitive demand increases significantly when using gait modification [32]. As expected, we observed a deterioration in the accuracy of performance in the gait task (increased FPA difference) during the dual task, particularly in week one. This effect is similar to the deterioration of gait performance with a dual-task observed in older adults during target stepping tasks [33]. Dual-task walking is associated with increased activation in the pre-frontal and pre-motor cortex, with strong correlations between the increased cerebral activity and the gait deficits [34]. Furthermore, dual-task performance is influenced by pain, with improvements in performance observed with a reduction in knee pain [35]. In our study, however, the self-reported baseline pain levels were low (median 2, IQR: 3 on a 10-point scale), hence we expect that pain did not influence dual-task performance.

After six weeks gait training, the effect of the dual-task (in comparison with the single-task, feedback condition) was diminished, indicating reduced interference of the dual-task and reduced cognitive loading. This can be explained by considering that as the motor task becomes more autonomous with increased practice time, the cognitive demand reduces; hence the dual-task (Stroop test) can be performed without interruption to the motor task. This effect is also known from psychological experiments, where practicing the requested task minimized the interference effect during a dual-task condition [36].

We must address certain limitations in this study. Firstly, the motivation of a KOA patient to adapt his/her gait may depend on the immediate effect of the gait modification on the pain level. In patients experiencing an immediate reduction in pain, we may expect that, the gait pattern would more quickly become “second nature”. Since the patients in this study had relatively low pain levels we recommend that future studies also include patients with higher pain levels, to confirm the anticipated response in these patients.

Secondly, evaluation of between-session changes in FPA may be subject to errors due to re-calibration of the motion-capture system and reapplication of foot markers. To reduce this error patients wore the same shoes for each session and we used a UV pen to draw marker

positions on the shoes.

Thirdly, time spent walking and training outside of the lab was not controlled and only assessed subjectively. This may lead to under- or especially over-estimation of the time spent walking and training. Given this, speculation on the effect of home training time on the performance is meaningless. Subjective assessment of the ease and normalness of use may have resulted in a positive bias (pleasing effect). We emphasize the need for future studies to use discreet wearable sensors, as in [27], to enable FPA measurements outside of the lab.

In conclusion, KOA patients reduced the FPA difference and increased the on-target steps after a six-week gait training program. Improved accuracy of performance and reduced interference of the dual-task in week six suggests a reduction in cognitive demand and evidence of slow learning. Despite this, the modified gait pattern was not fully autonomous after the training program. Future studies should consider home training with wearable technology to encourage full autonomy of the modified gait pattern.

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Conflicts of interest

None of the involved authors have any conflict of interests (personal or financial) to report.

Ethics

The procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Ethical approval for this study was granted by the Medical Ethics Committee of the VU Medical Centrum, Amsterdam, Netherlands in September 2015.

All patients provided written consent for their participation in the study, prior to the obtaining of any research data.

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