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Research article

Modification of knee flexion during walking with use of a real-time personalized avatar

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ABSTRACT

Visual feedback is used in different research areas, including clinical science and neuroscience. In this study, we investigated the influence of the visualization of a real-time personalized avatar on gait parameters, focusing on knee flexion during the swing phase. We also studied the impact of the modification of avatar's knee amplitude on kinematic of the knee of healthy subjects. For this purpose, we used an immersive reality treadmill equipment and developed a 3D avatar, with instantly modifiable parameters for knee flexion and extension (acceleration or deceleration). Fourteen healthy young adults, equipped with motion capture markers, were asked to walk at a self-selected pace on the treadmill. A real-time 3D image of their lower limbs was modelized and projected on the screen ahead of them, as if in a walking motion from left to right. The subjects were instructed to continue walking. When we initiated an increase in the knee flexion of the avatar, we observed a similar increase in the subjects' knee flexion. No significant results were observed when the modification involved a decrease in knee flexion. The results and their significance are discussed using theories encompassing empathy, sympathy and sensory re-calibration. The prospect of using this type of modified avatar for stroke rehabilitation is discussed.

1. Introduction

Motor behavior and adaptations during specific actions emerge from the interactions of the nervous system, the body and the environment [1]. These interactions are based on sensory integration and motor control [2]. Most of the related information is confirmed by the perception system with multimodal sensory integration [2, 3]. The integration of at least two inadequate data results in the generation of errors during information processing [4, 5]. In this case, the integrating system may choose to ignore the less weighted information as described in the sensory weighting model [6, 7], or may lead to an illusion of perception when both modalities have the same importance [8, 9]. These paradigms have been specifically studied for changing perception and behavior during target scoring [10, 11]. Two types of adaptations have been described. The first is a direct reweighting of the value of sensory information with rapid motor adaptation [12, 13]. The second is the long-term recalibration of sensory inputs, which results in a change in motor behavior over a long period of time after the illusion has stopped [14]. The illusory perception of one's own movements leads to the same type of observations for hand movements or eye-foot coordination [15, 16, 17]. Indeed, adaptive changes in egocentric localization and eye-to-foot coordination occur when a subject walks with prisms that generate illusions, without seeing his legs [16]. Integration is more specific when the perceived object is a subject in biological movement [18]. Indeed, when an observer perceives biological movement, the discharge of dedicated neural systems (related to empathy and sympathy, such as mirror neurons or the neural “ment” network) allows the understanding of an action and deducing the intention behind that action [19, 20]. In addition, these networks make it possible to manipulate spatial reference frameworks, through the coordination of embodied and unembodied perspectives [21], and the imitation of action [22, 23]. It has been hypothesized that during interaction, spontaneous imitation of an action with the mirror neural system was related to the correction of perceived error, suggesting that "the most likely cause of an observed action can be inferred by minimizing the prediction error at all levels of the cortical hierarchy that are involved during observation in action" [24]. The main argument for this statement is that for the motor cortex, observing an action and performing the same action are very similar

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events [22, 23, 24], especially when observing one's own movements [25]. This suggests that it may be possible to artificially adjust motor behavior by manipulating the perceived biological movement in real time during observation of the action. Virtual reality seems to be the ideal tool to generate such adjustments. Indeed, it creates a controlled environment where self-perception can be modified. Appropriate adjustments can be made so that cognitive processes lead to the generation of "wanted motricity" by providing subjects with a set of perceptual data on a "desired behaviour" [26]. This has been confirmed in many studies using biased feedback during in-game motor and cognitive tasks. Indeed, at the cortical level, the potential response of the motor cortex related to the EEG error varied in real time when the visual feedback on the kinematics of the upper limbs was modified [27]. In this study, the change in visual feedback was perceived as an error. However, the amplitude of the modification did not affect the error wave, suggesting that the perception of the amplitude of the error was made at another level of perception. At the kinematic level, motor behavior was also affected by modified feedback [28, 29]. In addition, it has been shown that the visual perception of the limbs in motion has a direct effect on movement strategies [30]. These recent results lead to the use of augmented feedback as a new rehabilitation method [31, 32, 33, 34]. Encouraging results have been reported for patients using virtual reality and real-time avatar during rehabilitation [35]. In addition, it has been shown that the observation of increased feedback leads to an improvement in knee flexion during a flexion/extension task [34]. However, in this study, the task was performed in a sitting position. Therefore, the results did not provide detailed information on the direct effect of an increased avatar on knee flexion in an upright position, during walking. In this study, we investigated whether an increased feedback influenced knee flexion in real time during the swing phase of walking, and whether the amplitude of the deformation decisively affected behavior. We developed a parametric and customized 3D avatar, whose knee flexion/extension could be modified in real time.

2. Materials

2.1. Avatar

The avatar was created and tested on the GRAIL system with D-Flow software (Motek Forcelink, Houten, Netherlands) which allows the user to interface with a motion capture system (10 infrared cameras Vicon Bonita with Nexus software - Vicon, Oxford Metrics, UK) and project an interactive virtual reality [36]. This combination allows subjects to interact with virtual reality in real time while walking on a treadmill.

The avatar represented the lower limb with 7 virtual cylindrical sticks, representing the feet, tibias, femurs and pelvis. Fifteen retroreflective markers were placed on anatomical landmarks following the Plugin Gait (PiG) marker set [37]. The dimensions and movements of the avatar limbs were calculated from the lengths, positions and angular information provided in real time in Vicon Nexus.

2.2. Real-time modification of the sagittal kinematics of the knee

In this study, we designed a method to differentiate the avatar's knee flexion from the subject's. The calculations for the change in the avatar's knee flexion were based on the subject's knee flexion. The modifications were performed in real time with the following equation:

$$\beta(i) = \alpha(i) + \omega * \frac{\alpha(i) - T}{\alpha max - T} \tag{1}$$

Where i was the frame number, $\alpha(i)$ the actual knee flexion of the subject, $\beta(i)$ the knee flexion of the modified avatar, ω the targeted level of variation, T the knee flexion angle at the beginning of the swing phase; and α the maximum knee flexion during walking.

The expression " $\omega * \frac{\alpha(i) - T}{\alpha max - T}$" in Eq. (1) represents the ratio of the wanted variation to the maximum of the curve in the ith frame. It is a percentage of the desired modification, ω, which evolves according to the progress in the step cycle. The T value was subtracted to adjust the variation ratio in the desired amplitude window. In this way, the differentiation in knee flexion between the avatar and the subject begins from the T value, at the beginning of the oscillating phase. At this moment the level of variation is 0%. This level increases as the step cycle progresses and reaches a maximum of 100% of knee flexion. Thus $\beta(i) = \alpha(i) + \omega$ when $\alpha(i) = \alpha max$. When the subject's knee flexion decreases towards T, the level of variation decreases again to 0% and $\beta(i) = \alpha(i)$.

The D-Flow software enables to record the entries of Nexus and an avatar. This allowed us to validate our method by comparing the avatar's motion based on Eq. (1) and the fixed αmax (movements of the avatar played), with the expected values of Eq. (1) and the actual values of the knee flexion peak for each walking cycle (movements recalculated from the raw Nexus data). The bending of the avatar's knee is given by the algorithm and recorded in real time in D-flow.

2.3. Algorithm

A specific algorithm was used for the bending behaviour of the avatar's knee during walking (Fig. 1). During the support phase, the avatar's knee flexion was the same as that of the subject. The knee flexion was modified during the oscillation phase according to Eq. (1). Our method involved an algorithm with oscillation phase detection. Since we were using motion capture, the "swing phase" state was considered true when the altitude of the toe marker (h(i)) became higher than its altitude during the subject's static calibration (h0), meaning that the foot was no longer on the treadmill. The knee flexion value (T) at this time is recorded. This phase ended when the subject's knee flexion was again below the T value. If $\beta(i)$ was below the T value, we included a minimum limit to avoid unnatural retroflexion on the knee joint. The limit was given by the value T:

if $\alpha(i) < T$, $\beta(i) = \alpha(i)$ and if $\beta(i) < T$, $\beta(i) = T$

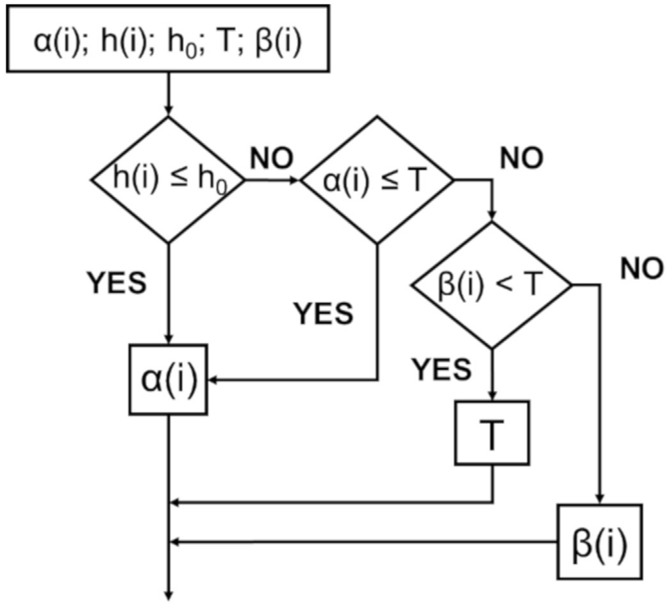

Fig. 1. Algorithm used to activate the flexion of the avatar's knee. $\alpha(i)$ is the flexion of the participant's knee at the ith frame. $\beta(i)$ is the flexion of the avatar's knee observed at the ith frame. h0 is the height of the toe mark during calibration and hi is the same value during walking at the ith frame. T is the value of knee flexion when $hi > h0$. This way, the avatar begins to change its behavior from subject only during the swing phase of the gait cycle.

3. Methods

3.1. Ethics statement

The ethical approval of this study was obtained from the Ethics Committee of the Department of Sport Sciences of the University of Nice (UNS-E18-003), and the written informed consent of all participants was obtained before the experiments.

3.2. Subjects

14 healthy young adults (age = 27.3 (6.2) years), 8 women (weight = 57.9 (7.3) kg; height = 1.62 (0.12) m) and 6 men (weight = 74.2 (6.3) kg; height = (1.79 (0.11) m) who gave their written and informed consent to this intervention, were equipped with retroreflective markers and walked on a treadmill.

3.3. Stimulus

The avatar was projected on the screen, so as to allow a sagittal view of his movements when the subject walked on the treadmill. The virtual character was always in the center of the screen and seemed to walk from left to right in a three-dimensional environment that flowed in the opposite direction of progression.

3.4. Procedure

First of all, the values h0 and αmax had to be configured as constant inputs to feed the algorithm. In this regard, we performed a static calibration of the subject using Vicon Nexus to determine the initial height of the toe marker, h0.

Then, during a familiarization phase by walking on the treadmill at a speed considered normal, at 1.3 m.s-1 without any projected images, the peak of the knee flexion curve, αmax, was automatically determined (absolute maximum of a curve).

Immediately afterwards, the subjects walked on the treadmill with the visual stimulus. Subjects were not aware of the nature of the stimulus. They were specifically asked to follow two rules:

> "Walk naturally on the treadmill until you meet the visual end signal."
> "Do not interact with the experimenter in any way."

18 values from ω were tested (from -40° to +45°; step: 5°). The avatar remained configured with each ω tested for 1 min. Each of these situations occurred 3 times randomly during the experiment following a simple randomization procedure (computerized random numbers). Raw data and algorithm results were recorded. Between each 1-min trial, the avatar was removed from the scene for 10 s.

4. Analysis

4.1. Algorithm

The expected values were calculated by applying the algorithm to Nexus raw data. In order to obtain the exact prediction, we used the exact value of the knee flexion peaks for each walking cycle. The avatar's knee flexion was calculated using a maximum value of α for all walking cycles. The data (predictions and avatars) were divided into normalized walking cycles into percentages of progression. During the walking cycle, the root mean square error (RMSE) was calculated between the prediction and the actual realization of the avatar recorded in D-Flow. The values of the coefficient of determination (R^2) indicated the ability of formula (1) to predict the bending of the avatar's knee when activated by human walking. For each of the 9 angles tested (-40° to +40°; step: 10°), 40 walking cycles were analyzed. The RMSE and R^2 were calculated using Statistica (StatSoft, Tusla, Oklahoma, USA). Mean and standard deviation calculations were performed with Matlab (Mathworks, Natick, Massachusetts, USA).

4.2. Walking with a modified avatar

For each angle tested, a repeated analysis of variance was performed to determine if there were any differences between the three iterations. For each side and for each tested angle that was repeatable (r-ANOVA, $p > .05$), a paired Student T-test with control sample was applied in Statistica to compare the knee flexion of the participants when the kinematics of the avatar was changed or unchanged. The control sample included knee flexion for subjects walking with the avatar with +0° modification.

In order to define the variability of the knee flexion amplitude during swing phase for each condition, we calculated the following coefficient of variability (CV) of knee flexion: $CV = \sigma/\mu$. Where σ and μ were respectively, the mean and standard deviation of knee flexion.

5. Results

All experimental data from this study are available as supplementary content in the document named Data.xlsx.

5.1. Algorithm

The predicted and measured avatar knee flexions were very similar (Fig. 2). Concerning the overall shape of the curves, a visual break could be observed when ω was less than -30°.

The mean and maximum values of the RMSE were higher for large variations (RMSEmax = 0.83°). The prediction was accurate (R^2min = 0.97) without error when ω = +0° (Table 1).

5.2. Effect of the modified real-time avatar on subjects' knee flexion

In this section, all of group of data were normally distributed, thus met the prerequisites for parametric tests.

For the three iterations of the same ω during the experiment, there were statistical differences in the participants' object knee flexion for ω = -15, F(2.26) = 8.53, p = 0.001 and ω = 5, F(2.26) = 6.58 p = 0.005 (Tables 2 and 3).

Walking with a modified avatar had no effect on knee flexion when $\omega < 0°$. The bending of the knee Object was positively affected when $\omega > 30°$. There was a significant difference in knee flexion between ω = 0 (M = 65.54, SD = 2.24) and ω = 30 (M = 67.13, SD = 2.43), conditions t(13) = 2.52, p = 0.03. Knee flexion was also higher for ω = 35 (M = 66.87, SD = 1.57), t(13) = 2.93, p = 0.01; ω = 40 (M = 66.45, SD = 1.97), t(13) = 2.26, p = 0.04 and ω = 45 (M = 67.01, SD = 2.87), t(13) = 2.21, p = 0.045. The flexion of the controlateral knee was not significantly altered throughout the session (Fig. 3).

The variability in controlateral knee flexion (CV = 7.2%) was higher than the Object knee flexion (CV = 3.3%) (Table 4).

6. Discussion

The movements of the avatar were correctly following our models predictions (rRMSE = 1.3%, R^2 = 0.97). While walking with modified avatar, the controlateral knee flexion was more variable (CV = 7.2%) than the object knee flexion (CV = 3.4%). When the knee flexion of the avatar was modified over 30°, the object knee of the subject significantly varied (ω = 30, t(13) = 2.52, p = 0.03; ω = 35 t(13) = 2.93, p = 0.01; ω = 40, t(13) = 2.26, p = 0.04; ω = 45, t(13) = 2.21, p = 0.045).

6.1. Algorithm

The affine variation function defined by Eq. (1) modifies the overall curve of the avatar's knee flexion (β(i)) according to that of the subject

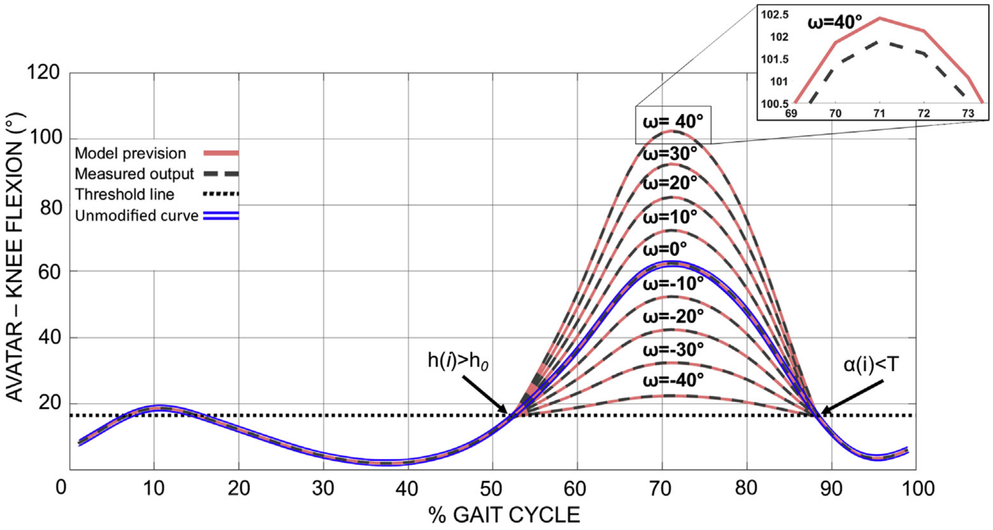

Fig. 2. Mean curve of the avatar's knee flexion for different values of ω. The motion of the avatar's knee flexion was tested for different values of real time modification (ω). The R^2 between Eq. (1) predictions and the actual movement of the avatar was very high ($R^2 = 0.97$).

Table 1
Model prediction error calculated with root mean square errors (RMSE) for each angle variation tested (ω). The relative root mean square (RMSE) was the ratio between the RMSE and the total amplitude of the sagittal movement of the avatar's knee. R^2 indicates the predictive power of Eq. (1) with a fixed αmax = 64.26°.

ω (°)	RMSE (°)				rRMSE (%)		R^2
	max	min	mean	SD	mean	SD	
-40	0,83	0,02	0,38	0,23	1,57	0,26	0.97
-30	0,62	0,01	0,28	0,17	0,82	0,18	0.98
-20	0,41	0,01	0,19	0,12	0,43	0,13	0.99
-10	0,21	0,01	0,09	0,06	0,17	0,08	0.99
0	0	0	0	0	0	0	1
10	0,21	0,01	0,09	0,06	0,12	0,08	0.99
20	0,41	0,01	0,19	0,12	0,23	0,15	0.99
30	0,62	0,01	0,28	0,17	0,3	0,18	0.98
40	0,83	0,02	0,38	0,23	0,36	0,23	0.98

(α(i)). Thus, the overall shape of the sagittal kinematic curve of the avatar's knee followed the subject's physiological behaviour. However, when the modification was very negative (ω < -30°), the deformation caused an unusual movement of the knee flexion. Indeed, for these ω values, there was a "break" in the curve that radically changed shape when the threshold value (T) was reached (Fig. 2). The RMSE errors between the prediction of the method and the actual kinematics of the avatar were less than 0.83° (Table 1) which is satisfactory (rRMSE = 1.3%, $R^2 = 0.97$). Indeed, knowing that the avatar was created to interact with perception, an error of less than 1° on an avatar with cyclic motion of 62° will hardly be noticed by the moving subject [38].

6.2. Effect of the modified real-time avatar on subjects' knee flexion

In this study, instructions were given to facilitate the transposition of the reference framework and the change of point of view [23]. We wanted the subjects to focus on their interaction with their own avatar. The first aim of the instructions was to draw the subjects' attention to the gait itself and to encourage them to continue walking until the "goal" is reached. The second aim was to make the subjects aware of the cinematic link between them and their avatar. Indeed, as the experimenter said "...you reach..." instead of "...the avatar reached...", the subjects would expect the avatar to move in the same way. By inhibiting interaction with

Table 2
Repeated anova test (r-ANOVA) comparing object knee flexions, for the three iterations of ω.

ω	Iteration 1		Iteration 2		Iteration 3		r-ANOVA	
	Mean	SD	Mean	SD	Mean	SD	F(2,26)	P value
-40	65,68	1,95	65,68	1,95	65,7	1,94	0,07	0,93
-35	65,77	2,07	65,77	2,09	65,84	1,96	0,62	0,55
-30	65,83	1,9	65,89	1,85	65,73	2,03	2,27	0,12
-25	65,97	2,09	66	2,06	66,01	2,2	0,34	0,72
-20	65,52	2,72	65,46	2,71	65,62	2,82	1,61	0,22
-15	66,06	2,08	66,11	2,08	65,91	2,06	8,53	0,001*
-10	65,72	2,08	65,71	2,06	65,83	2,14	2,67	0,09
-5	65,63	2,1	65,61	2,08	65,7	2,09	1,17	0,33
0	65,57	2,28	65,55	2,29	65,5	2,17	1,1	0,35
5	65,71	2,38	65,72	2,35	66	2,24	6,58	0,005*
10	65,92	1,67	65,86	1,71	66,01	1,68	2,21	0,13
15	65,86	1,69	65,88	1,69	65,76	1,79	2,15	0,14
20	65,88	1,82	65,88	1,83	65,83	1,81	0,4	0,68
25	65,8	1,69	65,82	1,7	65,79	1,59	0,04	0,96
30	67,14	2,45	67,17	2,42	67,09	2,44	2,62	0,09
35	66,91	1,56	66,91	1,5	66,78	1,68	2,28	0,12
40	66,49	1,97	66,48	1,95	66,4	1,99	0,93	0,41
45	67,03	2,84	67,04	2,82	66,97	2,96	0,25	0,78

*is significant at $p < .05$.

Table 3
Repeated anova (r-ANOVA) test comparing the controlateral knee flexions, for the three iterations of ω.

	Iteration 1		Iteration 2		Iteration 3		r-ANOVA	
ω	Mean	SD	Mean	SD	Mean	SD	F(2,26)	P value
-40	65,8	4,06	65,82	3,99	65,78	4,11	0,3	0,75
-35	65,52	5,1	65,61	5,1	65,53	5,05	2,43	0,11
-30	65,27	4,48	65,3	4,54	65,32	4,58	0,86	0,44
-25	65,46	4,49	65,47	4,53	65,48	4,49	0,09	0,91
-20	65,56	4,64	65,53	4,64	65,63	4,62	2,94	0,07
-15	65,37	4,53	65,37	4,53	65,33	4,61	0,38	0,69
-10	66	4,55	65,98	4,57	65,92	4,5	1,93	0,17
-5	66,24	4,95	66,19	4,96	66,21	4,93	0,53	0,59
0	65,98	4,76	66,04	4,78	66,03	4,92	0,82	0,45
5	65,53	4,72	65,51	4,75	65,52	4,75	0,25	0,78
10	65,1	5,13	65,15	5,1	65,14	5,16	0,55	0,58
15	65,53	4,88	65,54	4,85	65,56	4,86	0,33	0,72
20	66,07	4,97	66,05	4,95	66,06	4,96	0,12	0,89
25	65,81	4,7	65,76	4,67	65,75	4,63	0,96	0,4
30	65,76	4,67	65,77	4,66	65,82	4,68	1,29	0,29
35	66,27	4,66	66,3	4,65	66,27	4,64	0,26	0,78
40	65,86	5,32	65,85	5,3	65,81	5,27	0,89	0,42
45	65,93	4,69	65,89	4,65	65,93	4,66	0,45	0,64

*is significant at $p < .05$.

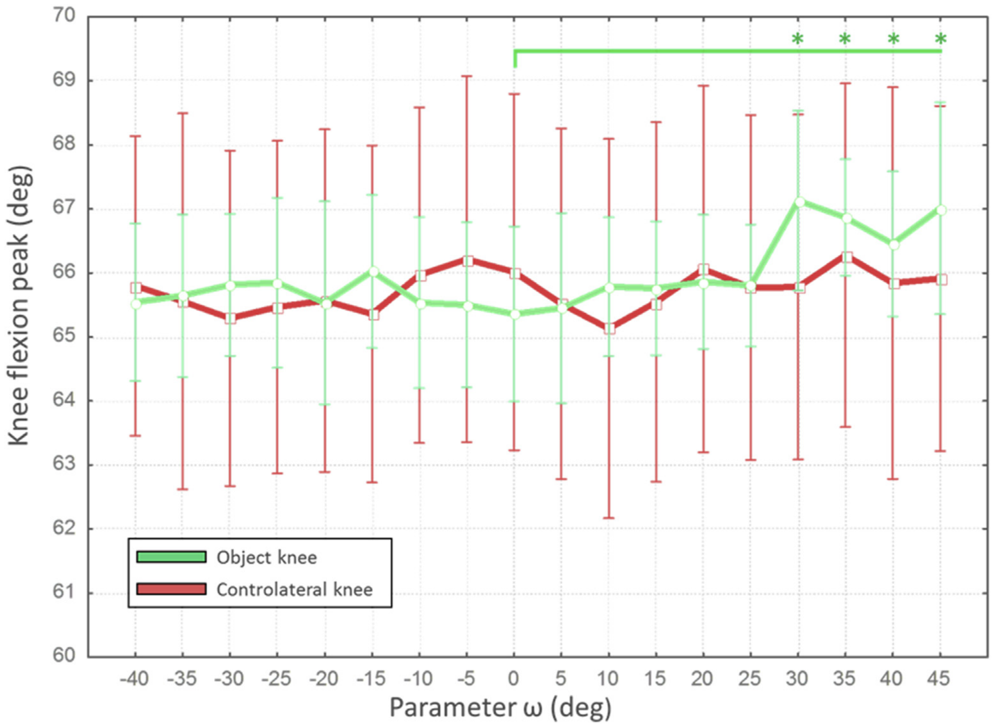

Fig. 3. Object and controlateral knee flexion peaks of subjects, in degrees, while walking on the treadmill with modified avatar. $N = 14$; Mean ± 0.95 Confidence interval; * is significant at $p < .05$. The object knee significantly varied when a modification of the knee flexion upper than 30° was applied. There was no significant change in controlateral knee flexion during the experimentation.

the experimenter, the second instruction aimed to get the subjects to focus on their own avatar.

For three iterations of the same angle tested ω, the flexion of the knee object was significantly different during walking for two values ($\omega = -15$, and $\omega = 5$), indicating that the measurement was not reproducible for these two values (Table 2). Therefore, knee flexion on both sides was tested for each value of ω, but the results for $\omega = -15$, and $\omega = 5$ will not be interpreted. During the experiment, the subjects changed their knee flexion. However, the amplitude of the variation was small (1.59°, $p < 0.05$). We explain this by the instruction given to the subjects to walk naturally, i.e. without forcing a movement. It is then normal not to observe large variations. Since the instructions were to walk naturally, and to reach the goal, these slight modifications meant that most subjects had not changed their behaviour voluntarily. These changes did not take place significantly when ω was less than 30°. Meanwhile, the controlateral flexion of the knee was not modified throughout the experiment (Fig. 3). This can be discussed with two additional considerations. The first is related to error correction and reweighting. In this experiment, we intentionally created a discrepancy between visual (AVATAR) and proprioceptive (subject) data regarding knee flexion during walking on a treadmill. We suggest that at first, the subject integration system noticed the shift [27]. Subsequently, the proprioceptive information had to be reweighted to match the visual input [11]. During the reweighting process, the subjects' prediction system was disrupted, leading them to modify their knee flexion [12, 17].

Table 4
Coefficient of variation of knee flexion during walking with real-time modified avatar.

ω (deg)	Object Knee CV	Controlateral Knee CV
-40	0,033	0,062
-35	0,033	0,078
-30	0,029	0,069
-25	0,035	0,069
-20	0,042	0,071
-15	0,031	0,07
-10	0,035	0,069
-5	0,034	0,075
0	0,036	0,073
5	0,039	0,072
10	0,029	0,079
15	0,028	0,074
20	0,028	0,075
25	0,025	0,071
30	0,036	0,071
35	0,024	0,07
40	0,03	0,08
45	0,043	0,071

The other part of this behaviour is in line with the change of reference framework and spontaneous imitation. Indeed, when walking on the treadmill, the avatar was seen perpendicular to the direction of movement. Without a systematic change in the frame of reference, it would have been impossible for the subjects to recognize which side was modified in real time. Thus, both knees would have been modified or not in an undifferentiated way. This would lead to two possible situations. Either both knees would be affected or random effects would erase differences on the object or controlateral knee. We suggest that the “ment” network system (allowing the change of frame of reference), and the system of mirror neurons (involved in imitation), are both involved in these specific variations [22, 23]. According to previous theories, and because of the lateral dependent effects that implied a change of referential, the phenomena observed here seem to be more related to empathy than to sympathy, which does not imply manipulation of the referential. However, there was no direct evidence on the specific pathways that were activated during this experiment.

A non-obvious element to discuss is the absence of significant differences when ω was negative. Indeed, since the subjects' behaviour changed when they walked with a modified avatar at $\omega > 30^\circ$, we would have expected the subjects to vary their knee flexion also for negative angles because of the visual disturbance in the feedback [39]. We suggest that, since walking on the treadmill at forced speed is an uncomfortable situation and lowering knee flexion deteriorates balance, resulting in a risk of falling after missing a step [40], the central system does not take into account the inadequacy of afferences for negative angles. A second possibility relates to the "unnatural nature of the walk" aspect of the avatar when $\omega < -30°$. Indeed, as shown in Fig. 3, the curves change radically in direction when the T value is reached, which could cause a break during observation and cause the avatar to fail self-identification [25, 41, 42]. This failure could let the subjects walk without correcting their own knee flexion. Overall, and according to the last observations, the absence of modification of knee flexion when walking with negative angles does not discredit the hypothesis of the implication of empathy and sympathy.

Finally, over all the walking cycles analyzed, the difference between the values of the coefficient of variation (CV) for object bending and controlateral knee bending is significant (Table 4). Overall, the controlateral standard deviation was greater than that of the object. We suggest that during the walk, subjects focused on and synchronized with the modified knee, which reduced its overall variability unlike the controlateral knee.

This study mainly corroborates previous results on global movements and rhythmic synchronization with other humans or avatars [43]. The contribution of this study was to observe the positive effect of a modified personalized avatar on the subject's knee flexion during walking on the treadmill, when subjects were asked to walk normally.

6.3. *Perspectives: potential implications of directed augmented feedback*

The avatar presented was created using specific tools (Nexus and D-flow), and the equation of variation was tested on knee flexion only. However, the properties of the variation function (1), which depends directly on the modified parameter, make it potentially usable for any other limb during a cyclic task. Indeed, since the algorithm uses a threshold, to enable and disable, a maximum based on a percentage of the peak of the curve, and the value of the curve itself, then it is possible to increase or decrease any curve that looks like a bell curve. For example, the sagittal movement of the hip can be modified with the same algorithm. In addition, for the purpose of further studies, the foot toe height detector proposed here may be replaced by any other threshold value. These possibilities combined with the encouraging results in this study might be used to develop rehabilitation for patients with weakened limbs (for example: post stroke patient, Children with cerebral palsy…), with gait training based on imitating an enhanced interactive avatar [35, 44, 45]. However, further work involving patients is needed because it is not clear whether they can respond to the avatar's biofeedback to modify their gait.

Further experiments would also be required to determine from which angle subjects notice that the avatar does not reproduce their exact movement. Moreover, this would make it possible to know whether the change in motor behaviour appears to be at the same amplitude of modification as that which would be noticed by the subject [27].

These experiments would help determine an optimal deformation of the avatar to obtain the best results with patients who need stimulation during gait rehabilitation. Post-stroke patients with knee stiffness could benefit directly from a real-time self-monitoring avatar with increased or reduced knee flexion, especially if they are in the chronic phase of their disability. The increased avatar could interact with motor behaviour by accelerating the phenomenon of learning motor tasks [31] combined with telepresence [46]. In studies on the pathological subject, we would recommend designing an avatar as a perceptual tool in the first place so that the patient can fully appropriate his environment. In a second step, the real-time modification of the avatar would lead the subject to correct himself because the tool will have profoundly changed his way of interacting with his own reality [26]. In a broader perspective, the use of this tool allows new possibilities for studying walking involving sensory disturbances of the embodied simulation [47].

6.4. *Limitations*

Although the study is based on several theories, the results do not clearly confirm the underlying mechanisms of behaviour change. More specific protocols (fRMI, EEG) should be established to confirm cortical mechanisms during observation of the modified avatar. This study was not conducted directly on patients, which only gives us indirect clues about the positive effects of the avatar on rehabilitation.

7. Conclusions

This study provides reliable evidence that the presence of a modified visual feedback during walking influenced knee flexion during the swing phase. In this case, since the change in knee flexion was small and only for the increased feedback, we suggest that the reweighting of visual and proprioceptive data is involved in the observed phenomena. The fact that the adaptation of knee flexion was laterally dependent indicates that attention was spontaneously directed to the avatar's modified knee. Moreover, knowing that the avatar was seen from the side, this dependence showed that the patient was working on a referential change. However, this study does not provide direct evidence of the theory of empathy, although its results may feed this theory as indirect indicators. Finally, this spontaneous adaptation can be used and enhanced during knee flexion rehabilitation.

Declarations

Author contribution statement

H. Agopyan: conceived and designed the experiments; performed the experiments; contributed reagents, materials, analysis tools or data; wrote the paper.

J. Griffert, T. Poirier: conceived and designed the experiments; contributed reagents, materials, analysis tools or data; wrote the paper.

J. Bredin: conceived and designed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

Data associated with this study is available as supplementary content, in the "Data.xlsx" file.

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