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ORIGINAL ARTICLE

Increasing Patient Engagement During Virtual Reality-Based Motor Rehabilitation

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Abstract

Objective: To investigate the influence of different design characteristics of virtual reality exercises on engagement during lower extremity motor rehabilitation.

Design: Correlational study.

Setting: Spinal cord injury (SCI) rehabilitation center.

Participants: Subjects with SCI (n=12) and control subjects (n=10).

Interventions: Not applicable.

Main Outcome Measures: Heart rate and electromyographic activity from both legs at the tibialis anterior, the gastrocnemius medialis, the rectus femoris, and the biceps femoris were recorded.

Results: Interactivity (ie, functionally meaningful reactions to motor performance) was crucial for the engagement of subjects. No significant differences in engagement were found between exercises that differed in feedback frequency, explicit task goals, or aspects of competition.

Conclusions: Functional feedback is highly important for the active participation of patients during robotic-assisted rehabilitation. Further investigations on the design characteristics of virtual reality exercises are of great importance. Exercises should thoroughly be analyzed regarding their effectiveness, while user preferences and expectations should be considered when designing virtual reality exercises for everyday clinical motor rehabilitation.

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Rehabilitation after a spinal cord injury (SCI) or stroke is crucial to improve an affected person's participation in social and ecologic environments. Robotic interventions (ie, external orthopedic appliances that assist the movement of limbs) have become increasingly accepted in the field of rehabilitation. However, despite all the advantages that such robotic interventions may provide, robotic assistance allows patients to reduce their effort to actively participate during rehabilitation training.[1-3] Since this can negatively affect the outcome of therapy, increasing active participation during robot-assisted rehabilitation is of great importance.

The use of virtual reality (VR) in the field of rehabilitation has nowadays become increasingly popular. VR is not only able to provide patients with an external feedback about their motor performance, but also, through game-like scenarios, increase the overall motivation and engagement (ie, physical activity) during training.[4,5]

Most VR exercises, however, still remain simplistic and are not properly analyzed regarding their effectiveness for motor learning during therapy.[6] Hence, studies about VR in rehabilitation generally only assess the deployment effect (ie, the effect that using or not using VR has on engagement) instead of addressing the design characteristics that VR exercises should comprise in

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order to optimally enhance engagement. This could either be because there are no clear guidelines of how such exercises should be designed to ensure optimal motivation and enhance motor learning during rehabilitation,[6] or more generally, because nearly no research has been done on video games.[7-10] One concept, however, that frequently has been studied in association with media and video game entertainment is the notion of flow.[11]

The flow theory by Csikszentmihalyi[12] describes several elements that make an experience enjoyable. Flow is thought to arise if a person does an activity for the "sheer sake of doing it."[12(p4)] It can be seen as a state of total engagement, so rewarding that people are willing to expend a great deal of energy simply to be able to feel it.[13-15] Originating from studies about creativity, the flow theory has since been applied to many different research fields. Conditions for flow include (1) the perception that the difficulty of a task matches with the personal skill level, and (2) that the activity provides clear proximal goals and immediate progression feedback. With these characteristics given, one can enter a subjective state of engagement with (3) an intense (ie, focused) concentration on the task at hand, (4) a merging of action and awareness, (5) a loss of the awareness of oneself, (6) a sense of control over one's activity, and resultantly (7) a distortion of the temporal experience (ie, an altered sense of time). Hence, by deliberating on these components, analogies to video game enjoyment can clearly be identified.

The one component of flow that often is being mentioned in relation to VR-based exercises for rehabilitation is the concept of adjusting the level of difficulty of a virtual exercise to the capabilities of the patient.[16,17] This results in engaging and motivating experiences without the effect of getting patients stressed, causing them to lose their self-esteem. Although, the level of difficulty is of great importance, we believe that it should not be the only flow component to consider when designing VR exercises for rehabilitation.

The "model of therapeutic engagement" states that the willingness of a patient to engage and stay engaged during therapy depends on the perceived treatment benefits.[18] Hence, similar to the flow theory, the goal of a VR-based exercise should be made apparent to the patient, with an explicit explanation about the benefits that can be achieved. Since information about the progress toward reaching a goal is important, exercises should further provide frequent explicit feedback about a patient's current level and quality of movement performance.

Another component of flow is "a sense of control over one's activity." This, however, does not only imply that the VR exercise should react to the activity of the patient, but also that the patient knows how to properly interact with the VR environment. Since the general assumption in rehabilitation is that motor recovery has to be stimulated by a training that aims at the functions to be regained,[19] exercises should react to functionally meaningful motor performances.

List of abbreviations:

BDI II	**Beck Depression Inventory II**
EMG	**electromyogram**
LEMS	**lower extremity motor score**
RMS	**root mean square**
SCI	**spinal cord injury**
SCIM III	**Spinal Cord Independence Measure III**
VR	**virtual reality**
WISCI II	**Walking Index for Spinal Cord Injury II**

Finally, consideration should be given to supplementing VR exercises with competitive situations, although competition is not directly defined in the flow theory but is one of the basic components of intrinsically motivating activities.[20] Competition gives us feedback about our current performance compared with that of others, and at the same time, encourages us to continue training in order to remain competitive. Competition is not only part of our daily life but, in addition, can be seen as one of the most prominent mechanics of video games, or rather games in general.[8]

In summary, exercises for VR-based motor rehabilitation should (1) be able to adapt the difficulty of a virtual exercise to the capabilities of the patient, (2) provide explicit task goals, (3) provide frequent explicit performance feedback, (4) show functionally meaningful reactions to the motor performance of the patient, and preferably (5) allow the possibility to accomplish competitive training. We believe that the fulfillment of these design characteristics will cause not only a "merging of a patient's action and awareness," allowing a complete focus on the movements to control the exercise, but also an "altered sense of time." Since the degree of performance improvement is dependent on the amount of practice during therapy,[21] the latter effect may further reduce the perceived therapy time and thus increase a patient's willingness for longer and more frequent therapy sessions.

Therefore, in the current study, we assessed the influence of these design characteristics on the level of participation during lower extremity rehabilitation. In detail, we hypothesized that (1) VR exercises increase patient engagement only if they are interactive (ie, if they provide functionally meaningful reactions to the motor performance of the patients); (2) VR exercises with explicit task goals and frequent performance feedback increase engagement compared with VR exercises without; and (3) competitive VR exercises increase engagement compared with noncompetitive exercises.

Methods

Participants

Ten control subjects without any neurologic movement disorders (table 1) and 12 subjects with SCI (table 2) were enrolled in the study at the Paraplegic Centre of Balgrist University Hospital, Switzerland. The inclusion criterion for the subjects with SCI was to be able to stand upright for at least 30 seconds, with or without support. Subjects with both chronic (>1y postlesion) and acute (<1y postlesion) SCI were considered. Exclusion criteria were signs of depression, severe contractures or skin lesions in the lower limbs, osteoporosis, cardiovascular instability, uncontrolled spasticity that would significantly interfere with the movement of the lower extremities, acute medical illness, height >190cm, or weight >135kg. Control subjects were between 23 and 31 years of age (mean, 25.9±2.73y), whereas subjects with SCI were between 23 and 66 years of age (mean, 46.3±14.0y). In order to obtain an overview about the physiological conditions and level of depression of subjects with SCI, different assessments were conducted.

Mobility was quantified using the Walking Index for Spinal Cord Injury II (WISCI II; mean, 15.4±6.37)[22] and the mobility subscale of the Spinal Cord Independence Measure III (SCIM III; mean, 29.7±8.48).[23] Both WISCI II and SCIM III have been shown to be valid and reliable for patients with spinal cord lesions.[23,24] In the WISCI II, patients are evaluated on a scale from 0 to 20, where 0 indicates standing and walking are

Table 1 List of control subjects who participated in the study

Patient No.	Sex	Age (y)	Dominant Leg	Treadmill Speed (km/h)	Min/Max*
1	M	24	R	2.0	−800/800
2	F	24	R	2.0	−800/800
3	M	27	R	2.0	−800/800
4	M	30	R	2.0	−800/800
5	F	23	R	2.0	−600/600
6	M	26	R	2.0	−800/800
7	F	24	R	2.0	−600/600
8	F	26	R	2.0	−600/600
9	M	31	R	2.0	−800/800
10	M	24	R	2.0	−800/800

Abbreviations: F, female; M, male; Min, minimum; Max, maximum; R, right.
* Biofeedback thresholds.

impossible and 20 indicates normal walking capabilities.[22] In contrast to manually measuring the WISCI II, in the current study subjects with SCI gave oral feedback. SCIM III covers everyday tasks and considers the economic burden of disability. In this study, we assessed the subscale of mobility, where 0 indicates dependent in all areas and 40 indicates independency.[23]

Lower extremity functions were assessed using the lower extremity motor score (LEMS; mean, 35.3±12.0).[25-27] The LEMS is a subscale of the American Spinal Injury Association motor score, which is a widely accepted and applied measure to assess muscle strength.[28] It rates the strength of 5 key muscles in each leg. While a score of 0 indicates total paralysis, 5 implies normal strength. The overall score is then calculated by adding up all subscores.

Finally, the level of depression was measured using the Beck Depression Inventory II (BDI II; mean, 7.6±4.3).[29] The BDI II yields reliable, internally consistent, and valid scores that consist of 21 items, with each having a 4-point scale ranging from 0 to 3. Hence, the maximum total score of the BDI II is 63.[30]

Approval was obtained from the local ethics committee according to the International Conference on Harmonisation of Technical Requirements for Registration of Pharmaceuticals for Human Use Good Clinical Practice guidance. All subjects gave their written informed consent before participating in the study.

Gait orthosis

The study was performed using the driven gait orthosis Lokomat.[31,32,a] The Lokomat comprises 2 actuated leg orthoses that are strapped to the legs of the patient, and is used in conjunction with a body weight support system and a treadmill. The hip and knee joints of the orthosis are actuated by linear drives that are integrated into the exoskeleton. Force sensors in each joint measure the interaction torques between the orthosis and the patient. Measured signals are then used to calculate the so-called biofeedback values per step cycle. Biofeedback values characterize the degree of movement effort—that is, the performance or activity of the patient.[33]

Virtual reality exercises

In order to verify our hypotheses, different VR exercises were created using the Unity3D game engine[b] and projected in front of the subjects onto a screen with a 2-m diameter by using a beamer with a resolution of 1280×800 (WXGA-Projector VPL-SW535[c]). Tasks within the exercises were presented in a detailed virtual environment where subjects walked along a straight path in a natural, hilly landscape of varying flora. Bird and locust chirps were added as background sounds, to further increase the VR experience. Four exercises were implemented:

1. *Steady:* Subjects were walking along the path with a constant speed; that is, no interactivity with the virtual environment was possible.
2. *Speed:* The activity of the subjects in the orthosis (ie, their measured biofeedback values) was used to modulate the virtual

Table 2 List of subjects with SCI who participated in the study

Patient No.	Sex	Age (y)	Level of Lesion	AIS*	TSI (y)	Etiology	BWS (kg)	Treadmill Speed (km/h)	SCIM III	WISCI II	LEMS	BDI II	Min/Max†
1	M	23	C6	D	1.1	Traumatic	20	1.8	20	16	22	12	−200/200
2	F	47	T12	D	17.0	Traumatic	20	2.0	35	20	36	8	−200/200
3	M	59	C5	D	8.3	Traumatic	70	2.0	40	20	40	13	−200/250
4	F	62	T4	D	3.8	Nontraumatic	45	2.0	26	19	47	5	−200/100
5	M	66	T12	C	6.4	Traumatic	41	2.0	27	16	20	12	−300/300
6	M	64	C4	D	9.5	Traumatic	25	2.0	40	20	50	0	−500/500
7	M	39	C4	D	18.7	Traumatic	40	1.8	21	5	28	4	(−275/75)
8	M	37	T8	B	12.4	Traumatic	43	2.0	18	1	23	11	−250/50
9	F	49	C3	D	13.1	Nontraumatic	33	2.0	40	20	49	5	−300/300
10	M	39	C7	D	9.8	Traumatic	37	2.0	38	20	48	5	(−250/400)
11	M	30	T11	A	0.3	Traumatic	43	2.0	23	12	20	4	−500/500
12	M	40	T11	D	0.8	Nontraumatic	40	2.0	28	16	40	12	−300/100

Abbreviations: AIS, American Spinal Injury Association Impairment Scale; BWS, body weight support; F, female; M, male; Max, maximum; Min, minimum; TSI, time since injury.
* AIS classification: A, sensorimotor complete; B, motor complete; C, sensorimotor incomplete (>50% of key muscles below neurologic level with muscle grade less than 3); D, sensorimotor incomplete (≥50% of key muscles below neurologic level with muscle grade 3 or more).
† Biofeedback thresholds.

speed in the environment, as described below in further detail. More active participation resulted in faster virtual movement speeds.

3. *Sprint:* While the mapping of the activity to the virtual speed was the same as in the Speed condition, subjects were additionally informed about their average speeds over the last and second to last 100m. Results were presented using numeric values in kilometers per hour at the top of the screen, when subjects passed "distance indication signs" that were placed at the side of the path. An attentive audio cue was played to make subjects aware of this information. This allowed further performance comparisons.
4. *Race:* The activity of subjects was again mapped onto the virtual speed, similar to that in the Speed and Sprint conditions. The Race condition, however, included competition. Subjects had to compete with a virtual opponent walking next to them, in a race-like manner. In order to respect the design characteristic of adjusting the level of difficulty to the subjects' capabilities, the virtual opponent was programmed in such a way that it always stayed near the subject. This was achieved by mapping the subjects' speed onto the opponent, with a 5-second delay. In addition to the visual feedback of seeing the opponent, game-like, high-frequency "success" and low-frequency "fail" audio cues were played when subjects passed or were passed by the competitor, respectively.

Hence, while in the Steady condition, subjects had no interaction possibilities, the Speed, Sprint, and Race conditions allowed interaction through the subjects' activity in the gait orthosis, providing a "sense of control." Compared with the Speed condition, the Sprint and Race conditions further introduced challenging tasks with explicit performance goals. Finally, the Race condition included competition as an additional element.

Virtual speed mapping

The mapping of a subject's physical activity to the virtual speed was done by averaging the biofeedback values[33] of the hip joints during the swing phase of the last step. Averaged biofeedback values below a certain lower threshold resulted in a virtual speed of 0km/h, whereas those above an upper threshold resulted in a virtual speed of 10km/h (see tables 1 and 2 for minimum/maximum values). Averaged values between the thresholds were interpolated linearly. In control subjects, the thresholds were fixed for men between −800 and 800, and for women the thresholds were fixed between −600 and 600. To adapt to the varied capabilities of the subjects with SCI, they were asked at the beginning of the experiment to try to be as active and subsequently as passive as possible. The resulting minimal and maximal biofeedback values were then used as thresholds for the course of the experiment. In 2 subjects with SCI, the thresholds had to be slightly adjusted during the beginning of the experiment (indicated in table 2 using parentheses).

Study design

In total, the study design comprised 6 different conditions. These included the 4 previously described conditions (ie, Steady, Speed, Sprint, Race) with the addition of a start and end baseline. While the start and end baselines were always the first and the last conditions, respectively, the 4 other conditions were presented in a pseudorandom order; that is, while the Steady and Speed conditions were presented in a random order during the first half, the Sprint and Race conditions were randomly presented during the second half of the experiment. During the baselines, no VR environment was presented. Each condition was shown for 4 minutes. At the beginning of each condition, subjects were instructed for 10 seconds on what they should try to achieve during the course of the condition; for example, "try to walk actively" or "modulate the speed using your activity." To allow for rest between the different conditions, a relaxation period of 3 minutes followed each condition.

Measurements

Engagement can be defined as a construct that is driven by motivation and executed through active, effortful participation.[18] Since, in the current study, active participation results in increased muscle activity, we argue that electromyography can be used to measure engagement.[34,35] Hence, electromyographic activity was measured in both legs at the tibialis anterior, the gastrocnemius medialis, the rectus femoris, and the biceps femoris. In addition, biofeedback values of the gait orthosis at each joint during the stance and swing phases were recorded.[33] The physical load of the subjects was assessed through heart rate measurements.

Data acquisition and analysis

Electromyograms (EMGs) were recorded from bilateral proximal and distal leg muscles using surface electrodes.[d] The EMG signals were amplified (400 times), filtered (band-pass 10−500Hz), and sampled at 1500Hz. In addition, left and right heel strikes were recorded. The locomotor EMG signals of all recorded muscles were offset corrected, and EMG values were calculated as the mean root mean square (RMS) per condition of the stance and swing phases, respectively. Biofeedback values were calculated for each recorded stride (bilateral hip and knee during the stance and swing phases) and averaged per condition. Heart rate was measured using Polar WindLink[e] and a Polar WearLink[e] chest strap. Mean heart rate was calculated per condition. Data acquisition and analysis were both conducted on commercial personal computers. All statistical analysis and plots were generated using SPSS 19[f] and Matlab R2009b.[g] In order to compare the measured EMG results, the data of each subject were normalized to his/her individual start baseline. Since the biofeedback values were used to interact with the virtual environment, they were excluded from analysis. Start and end baseline did not differ significantly. Therefore, the end baseline was removed from data analysis. Because of the nonnormal distribution of the data, statistical analysis between all conditions was performed using a nonparametric Friedman test. If results were significant ($P<.05$), post hoc analysis between paired conditions was done using a Wilcoxon signed-rank test, with the level of significance corrected according to Holm-Bonferroni.[36]

Results

Heart rate

Post hoc analysis for subjects with SCI revealed significant differences between the Steady and the Speed ($P=.003$) and between the Steady and the Sprint conditions ($P=.006$) (fig 1A). In control subjects, statistical post hoc analysis showed significant

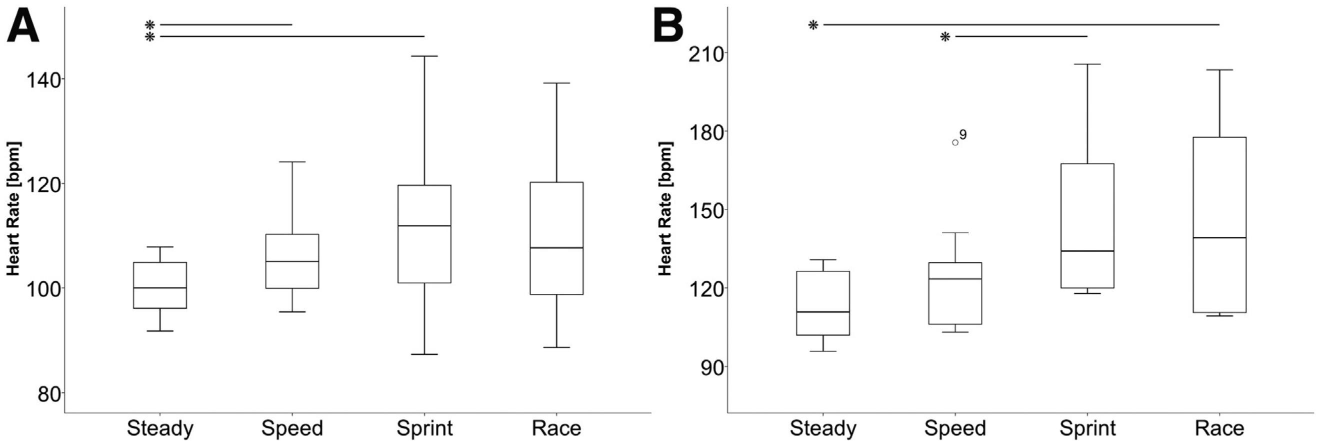

Fig 1 Heart rate of subjects with SCI (A, n = 11) and control subjects (B, n = 10), per condition, compared with the start baseline condition. Bottom and top edges of illustrated boxplots indicate the 25th and 75th percentile, respectively. Whiskers extend to 1.5 times the height of the box, or to the minimum or maximum values if no case has a value in that range. Outliers (o) have values that do not fall within the whiskers and are marked with an asterisk if their values are more than 3 times the height of the boxes different from the median (ie, extreme outliers). Abbreviation: bpm, beats per minute.

differences between the Steady and the Race ($P=.007$) and between the Speed and the Sprint conditions ($P=.009$) (fig 1B). One subject of the SCI group had to be removed from analysis because of recording issues with the chest belt.

EMG measurements

Biceps femoris

Post hoc analysis of the RMS values for the biceps femoris in subjects with SCI showed significant differences in the right leg during swing phase between the Steady and the Speed ($P=.013$), the Steady and the Sprint ($P=.003$), the Steady and the Race ($P=.004$), and between the Speed and the Sprint conditions ($P=.006$) (fig 2A). In control subjects, the only significant difference was found in the left leg during stance phase between the Steady and the Race condition ($P=.007$) (fig 2B). One subject with SCI had to be removed from the analysis of the right leg because of a loosened EMG electrode.

Gastrocnemius medialis

No significant differences were found in the post hoc analysis of the RMS values for the gastrocnemius medialis in subjects with SCI (fig 3A). In control subjects, significant differences were found in the left leg during stance and swing phases between the

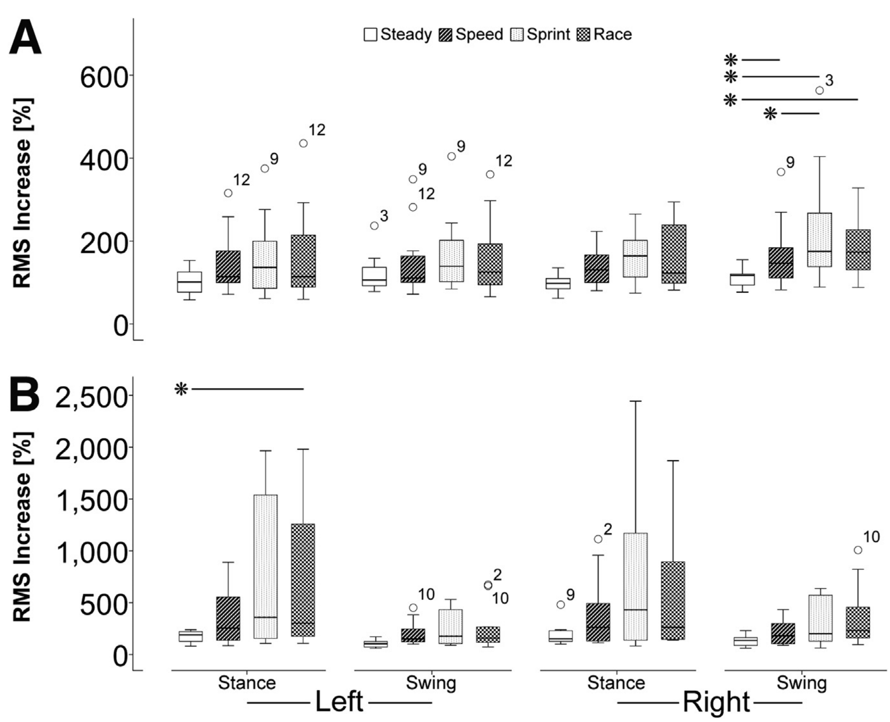

Fig 2 Normalized RMS values of EMG signals of subjects with SCI (A, Left n = 12; Right n = 11) and control subjects (B, n = 10) for left and right biceps femoris during stance and swing phases, per condition, compared with the start baseline (100%).

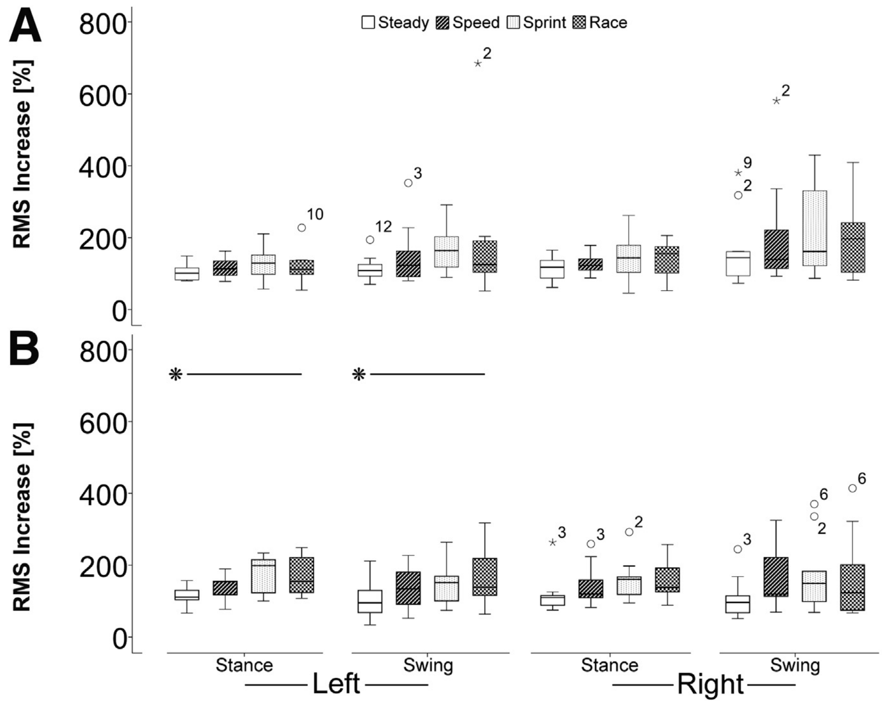

Fig 3 Normalized RMS values of EMG signals of subjects with SCI (A, n=12) and control subjects (B, n=9) for left and right gastrocnemius medialis during stance and swing phases, per condition, compared with the start baseline.

Steady and the Race conditions (*P*<.008) (fig 3B). One control subject had to be removed from the analysis because of a loosened EMG electrode.

Rectus femoris

Post hoc analysis of the RMS values for the rectus femoris in subjects with SCI showed significant differences in the left leg during stance phase between the Steady and the Speed (*P*=.003) and between the Steady and the Sprint conditions (*P*=.005). In addition, significant differences were found during swing phase between the Steady and the Speed (*P*=.002), the Steady and the Sprint (*P*=.006), and between the Steady and the Race conditions (*P*=.005) (fig 4A). In control subjects, post hoc analysis revealed significant differences on the left side during swing phase between the Steady and the Speed (*P*<.008), the Steady and the Sprint (*P*<.008), and between the Steady and the Race conditions (*P*<.008). On the right side, a significant difference was found during stance phase between the Steady and the Speed conditions (*P*<.008) (fig 4B). One control subject had to be removed from the analysis because of a loosened EMG electrode.

Tibialis anterior

Post hoc analysis of the RMS values for the tibialis anterior in subjects with SCI showed significant differences in the left leg during stance phase between the Steady and the Speed (*P*=.006), the Steady and the Sprint (*P*=.002), the Steady and the Race (*P*=.005), and between the Speed and the Sprint conditions (*P*<.008). A significant difference was found between the Sprint and the Race conditions (*P*=.023) in the left leg. During the swing phase of the left leg, a significant difference was found between the Steady and the Sprint conditions (*P*=.003) (fig 5A). In control subjects, post hoc analysis revealed significant differences on the left side during stance phase between the Steady and the Sprint (*P*=.009) and between the Steady and the Race conditions (*P*=.007). On the right side, significant differences were found during stance phase between the Steady and the Speed (*P*=.005), the Steady and the Sprint (*P*=.009), and between the Steady and the Race conditions (*P*=.009) (fig 5B).

Discussion

SCIs cause severe impairments of motor, sensory, and autonomic functions. Active participation during rehabilitation has been shown to promote cortical plasticity through cortical map reorganization.[37] Since the level of engagement influences active participation,[18] the aim of the current study was to compare whether different VR exercises, presented while walking in a gait orthosis, can influence the level of engagement of patients. We argued that an increase in engagement could be seen by an increase in muscle activity and heart rate. Because of possible autonomic dysfunction in subjects with SCI,[38] heart rate measurements were interpreted with caution. Since muscle activation patterns have been shown to be different during walking in a driven gait orthosis,[39] and subjects with SCI exhibit different patterns of muscle activity than control subjects, comparing electromyographic activity between the 2 groups as well as with electromyographic activity during normal walking was omitted. Hence, we compared differences in muscle activity between exercises.

Of all the findings, the most prominent effect was found between VR exercises that differed in providing functionally meaningful reactions to motor performance. Thus, our results show significant differences between interactive (ie, Speed, Sprint, Race) and noninteractive (ie, Steady) exercises, although these differences were not present in all muscles. The differences were most prominent during the swing phase of the left rectus femoris for both subjects with and without SCI. Since the virtual speed was controlled by the hip joints during the swing phase, these significant

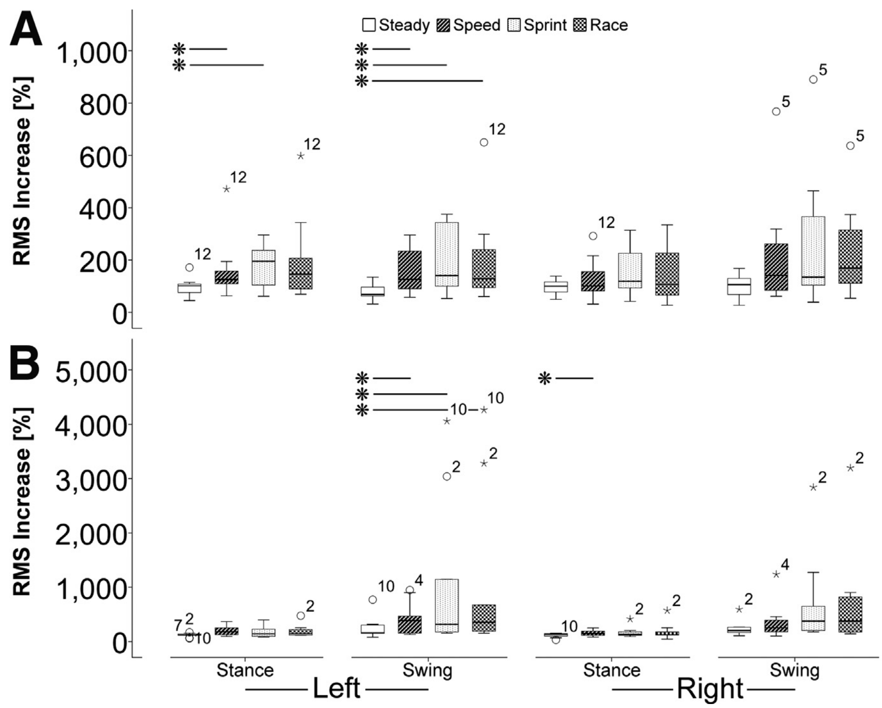

Fig 4 Normalized RMS values of EMG signals of subjects with SCI (A, n = 12) and control subjects (B, n = 9) for left and right rectus femoris during stance and swing phases, per condition, compared with the start baseline.

differences are in great favor of the first hypothesis (ie, that VR exercises increase patient engagement only if they are interactive). Considering the additional differences in heart rate, we argue that our first hypothesis can be confirmed. While previous studies[40,41] were already able to show that the addition of VR during walking in a gait orthosis increases muscle activity, we therefore were further able to verify that this increase only occurs if the deployed VR generates possibilities for interactivity. In addition to increased engagement, the deployment of interactive VR may additionally help to reduce the discomfort that today's gait orthosis can imply.[42] Hence, research has shown that interactive VR is capable of reducing pain.[43] This, however, is subject to further studies.

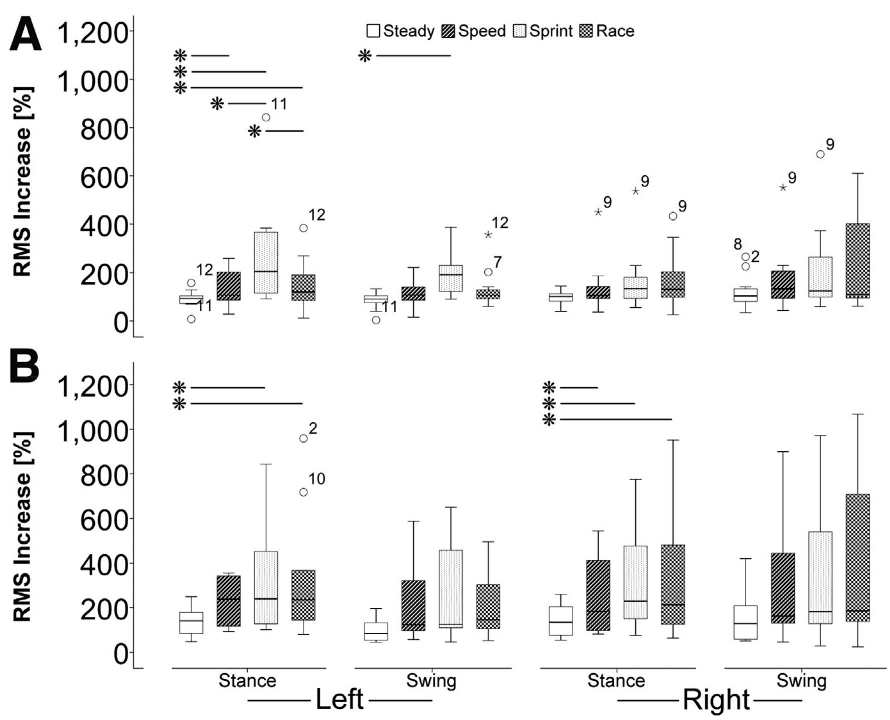

Fig 5 Normalized RMS values of EMG signals of subjects with SCI (A, n = 12) and control subjects (B, n = 10) for left and right tibialis anterior during stance and swing phases, per condition, compared with the start baseline.

In contrast to our first hypothesis, our second hypothesis (ie, that VR exercises with explicit task goals and frequent performance feedback increase engagement compared to VR exercises without) was not supported by our measurements. Thus, although significant differences were found between the Speed and Sprint conditions in the right biceps femoris and the left tibialis anterior of subjects with SCI, we argue that these findings are rather arbitrary and therefore not adequate to sustain the second hypothesis. A lack of increased engagement could be attributed to multiple reasons. Thus, since research has shown that it is possible to estimate self-motion through optic flow in real[44] and VR environments,[45] the immediate feedback gained through virtual velocity changes may potentially have sufficed subjects during the Speed condition to rate their current level of performance, thus reducing the need for further feedback mechanisms. The lack of explicit task goals in the Speed condition might additionally have encouraged a self-paced exploration of the VR environment.[8,46] Hence, while subjects were explicitly challenged to higher speeds in the Sprint and Race conditions, they might have produced similar ones in the Speed condition. Since research has shown that pursuing self-defined goals can have a substantial effect on the level of effort (ie, performance during a task),[47] the self-defined goal of exploring as much as possible of the VR environment may, therefore, have led to increased active participation.

Finally, in contradiction to the third hypothesis (ie, that competitive VR exercises increase engagement compared to noncompetitive exercises), there was only 1 significant difference between the Race and the Sprint conditions in the left tibialis anterior of subjects with SCI. Contrary to the hypothesis, the muscle activity in the Race condition was, however, lower. The most intuitive explication for this finding can be seen in the nature of the exercises themselves. Compared with the Sprint condition, we denoted the Race condition as competitive. However, while subjects were competing against a virtual opponent in the Race condition, they were competing against themselves in the Sprint condition. Since, during therapy, subjects with SCI mainly compare themselves to their own motor improvements,[48] they might have preferred the Sprint to the Race condition. In addition, although adapted to the abilities of the subject, the Race condition might have created a competitive pressure.[46] Because "social comparison" can have both beneficial and detrimental effects, subjects who were always ahead of the opponent may, therefore, have displayed higher active participation as a result of the satisfaction derived from mastering the challenge, whereas subjects who were always near or behind the opponent lost interest in the activity and reduced their effort to actively participate.[47] At last, similar to other studies,[40,49] subjects may have increased their activity once the opponent was near and decreased it again once the opponent was behind them. This might have led to an overall lower mean activity.

One can argue that our VR exercises might have been too similar to elicit different levels of engagement. However, apart from the fact that video game characteristics are rated differently,[50] studies[51,52] have further shown user and sex-specific preferences when it comes to video game playing. Hence, similar effects (ie, preferences of the subjects) could also have caused these inseparable results.

Study limitations

The 6 different conditions, presented for 4 minutes each, together with the relaxation periods of 3 minutes, resulted in a total duration length of roughly 40 minutes. This constitutes the maximum training duration that is usually suggested for therapy without having exhaustion effects (∼30−45min). Thus, although longer durations for each condition would have been favored, to allow subjects to reach a steady state, 4 minutes was the maximum that was possible. However, the presentation time of 4 minutes in the present study was longer than in other similar studies.[40]

The uneven distribution of significant differences between the left and right legs can be attributed to subjects being able to interact with the VR exercises by using both their hip joints during the swing phase. Therefore, subjects may have used their dominant leg more frequently or intensively. Unfortunately, this might have suppressed finding additional significant results. We, however, chose this approach to reduce the effort needed to interact with the VR environment and thus decrease the probability of early exhaustion. This limitation should be addressed when creating VR exercises for everyday clinical motor rehabilitation.

Despite having an identical virtual environment, exercises differed in the use of audiovisual feedback. Hence, compared with the Steady and Speed conditions, the Sprint condition used audiovisual cues to inform subjects about their average speeds, and the Race condition presented positive and negative audiovisual cues when subjects passed or were passed by the competitor, respectively. The addition of this additional feedback was part of the second hypothesis. Nevertheless, we cannot exclude that the differing types of audiovisual feedback given in the Sprint and Race conditions could potentially have had an additional effect on results.[10,53] Since the effects of differing audiovisual feedback on active participation during motor rehabilitation have so far, however, not been addressed, we currently cannot determine the degree of influence. Hence, this should be subject to further studies.

Finally, the number of subjects was limited. Additional subjects, especially in the SCI group, may have led to a more homogeneous distribution of age and level of impairment. Nonetheless, we do not believe that the rather heterogeneous distribution of age in the SCI group had an effect on the measured results. Hence, independent of age, subjects with SCI show high motivation to improve their motor skills.

Conclusions

By varying the design characteristics for VR exercises set forth in the introduction, we were capable of inducing different levels of engagement in subjects training with these exercises. Hence, the results of this study show that functional feedback is highly important for the active participation of patients during robot-assisted rehabilitation. Apart from showing that VR exercises have to be interactive, our results further suggest that it is crucial to take user preferences and expectations into consideration. Thus, user and sex-specific preferences or, for instance, the possibility of self-definable in contrast to predefined task goals, may all have a subjective influence on the resulting level of active participation. Finally, our findings highlight the importance of further investigations on the characteristics that VR exercises should comprise and, in accordance with Flores et al,[6] illustrate the need of thoroughly analyzing the effectiveness of VR exercises for motor rehabilitation. Hence, our future research efforts will be directed toward identifying additional VR characteristics, assessing their effect on patient preferences and their ability to increase the active participation of patients during therapy. In addition, our next steps will include a training study to investigate the long-term clinical effectiveness of VR exercises during SCI motor rehabilitation.

Suppliers

a. Hocoma AG, Industriestrasse 4, CH-8604 Volketswil, Switzerland.
b. Unity Technologies, 345 Broadway St, Ste 200, San Francisco, CA 94133.
c. Sony Corp, 1-7-1 Konan, Minato-ku, Tokyo 108-0075, Japan.
d. Noraxon U.S.A. Inc, 15770 North Greenway-Hayden Loop, Ste 100, Scottsdale, AZ 85260.
e. Polar Electro Oy, Professorintie 5, FIN-90440 Kempele, Finland.
f. IBM Corp, 1 New Orchard Rd, Armonk, NY 10504.
g. MathWorks, 3 Apple Hill Dr, Natick, MA 01760-2098.

Keywords

Gait; Motor activity; Rehabilitation; Spinal cord injuries; Virtual systems

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