The Use of Virtual Reality-based Dynamometer Training to Enhance Selective Joint Torque Control in a Child with Cerebral Palsy

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Abstract

Virtual reality (VR) environments present nowadays a powerful tool for visual feedback in assessment and training programs of rehabilitation. Designing appropriate target-oriented tasks may enhance the rehabilitation options available in biomechanical dynamometry. The subjects are motivated to achieve a goal in the VR environment, and therefore, their performance often increases. This adds a significant value to the evaluation of the subject’s capabilities and design of the appropriate training program that may enhance the selective joint torque control in children with cerebral palsy. In this paper, we suggest a VR environment that offers motivation for maximal joint torque generation and VE for joint torque control training. A dynamometer with torque sensor and axis motor was used in the process and enabled biomechanical information, i.e. knee joint torque and surface electromyography, assessment during the target-oriented VR based task. A 12-year old child with cerebral palsy participated in the case study. The protocol consisted of three consecutive days of virtual reality-supported training under various conditions, like task velocity and difficulty level. Our data suggested that there were improvements in the knee joint torque tracking and increased target hit score regardless of the task difficulty level. Besides the improvement of the knee joint torque control, presumably more muscle power could be generated, resulting in more successful performance at targets where high joint torque was required. Apparently high level of motivation has been noticed. The advantages of using VE for rehabilitation services were shown in variability of attractive target oriented tasks, repeatability and highly motivated subjects. Hereby, a VR environment guided dynamometer based assessment and training for single joint was demonstrated. The promising outcomes call for longer training period and clinical evaluation of modern therapeutic approach.

Keywords: Virtual reality (VR), Rehabilitation, Dynamometry, Cerebral palsy, Motor control

1. Introduction

Nowadays the Western world is progressively implementing recent technologies into rehabilitation of children with cerebral palsy (CP), a non-progressive clinical syndrome caused by injury to the immature brain. The prevalence of CP within European Union is around 2.5 per 1000 live births [1]. Cerebral palsy frequently affects and changes movement and/or postural patterns, depending on the severity of the disorder. The consequence of the CP is visible in an inability to voluntarily control and coordinate muscles, resulting in a poor selective motor control. The usual muscle activation, co-contraction to achieve certain biomechanical functions such as coordinated limb movement is disrupted and causes deficits in gait and posture. During the child’s growth, the gait is considered as one of the most critical activities due to possible bone deformation [2]. Gait abnormalities are often due to muscle shortening, spasticity and contractures, disorders in central nervous system, poor selective muscle control or also muscle weakness. The muscle weakness caused by biomechanical shortening can be identified by voluntary isometric contractions using dynamometry [3], while surface electromyography (EMG) enables identification of muscle (co)contractions and timing, which both affect the neuromuscular system [4]. Besides muscle performance identification, isometric and isokinetic dynamometry may also play an important role in muscle re-strengthening training [5], spasticity evaluation [6], and selective motor control training [7].

The motor control training and muscle strengthening are often performed within a clinical environment with predefined tasks and real objects. In contrast, recently developed technologies enable development of similar tasks in a virtual world, using computer graphics. The tasks created within the virtual reality (VR) environment offer a capability to provide
real-time feedback to the subject during practice. Subjects can see the effect of their action immediately after the intervention and change the strategy to achieve the directed goal [8]. Such goal presented in the VR environment may have similar rehabilitation effect as the tasks applied in the real world [9]. Besides augmented feedback, the VR can also enable selective motor control learning to the people with disabilities [10]. The motor learning is defined as a sensory perceptual mechanism by which a new motor skill is learned. An essential component of the motor learning is feedback, which could in the real world be provided by the physiotherapist or in the virtual world be provided by visual scenery. In contrast to the task performed in the real environment, the virtual environment can be easily changed, adapted to the subject’s needs, speed and level and keeping all the modifications of eventually complex virtual scenarios within controllable and reproducible limits. Successful applications have been shown in stroke patients [11,12].

In children with CP the virtual exercises should be attractive to maintain a high level of motivation, which is necessary for efficacy of the VR based training [13]. Bryant et al. [14] have shown a VR application of ankle angle control retraining to achieve better heel strike, and, like many other authors [14,15] applied position-to-position transformation of assessed information into the VR object. They reported on increased range of motion in ankle dorsiflexion, better control and greater interest in exercise performance when using the VR system than stand-alone exercise.

In this paper, we propose a different, unique approach, using a joint torque-to-VR object position transformation instead of the commonly used joint position-to-VR object position transformation. Furthermore, the VR task was target-oriented, requiring the subject to carry out a specific action applied to the modified version of the commercially available dynamometer. The subject was required to learn how to control the generated joint torque with a specific muscle group. We hypothesized that the training with real-time feedback using VR task would motivate the participating subject to improve tracking of the targeted reference and thus also facilitate an improvement in selective joint torque control. In children with CP the improvement in joint torque control may also reflect in positive changes of gait pattern, which is of great importance to the child’s growth and development [16].

2. Materials and methods

2.1 Subject

The 12-year old boy with cerebral palsy (CP II, spastic diparesis, 149 cm height, weight 48 kg, functional electrical stimulation 1-ch peroneal nerve 1 hour/day, crouch gait, poor selective motor control), a patient of the rehabilitation hospital, voluntarily participated in the case study due to his good cognitive capabilities. The child had no prior experience with any VR(VE)-based tasks. The methodology was approved by the local ethics committee, and the subject’s parents gave informed consent.

2.2 Equipment

The system consisted of a VR display, a personal computer for data assessment and control and a dynamometer (Fig. 1). The VR environment tasks were programmed in VRML 2.0 and projected to the display via Internet Explorer™ with the blaxxun plug-in [17]. The graphical interface, data assessment and communication with VR objects were programmed in Matlab (The MathWorks, Inc., Natick, MA, USA [18]). The interface communicated via serial interface with the Biodex System 3 dynamometer (Biodex Medical Systems, NY, USA) in isometric mode, providing angular position of the lever and torque data on analog output. The analog output data were sampled and filtered with multifunction DAQ board (NI-PCI- 6259, National Instruments, Austin, TX, USA) before the transformation into kinematic position and orientation were applied and transferred to the objects in the VR environment. Simultaneously, the muscle activity of the knee extensors was assessed by electromyography, MyoSystem 2000 (Noraxon Inc., AZ, USA) using Red Dot™ Monitoring Electrodes with Foam Tape (3M™, St. Paul, MN 55144-1000, USA) and Sticky Gel for single use.

2.3 Tasks in virtual reality environment

The tasks applied as the real-time feedback in the dynamometer-based selective motor control training needed to be fun [8] to attract a child’s attention, but rather simple enough to allow quick familiarization and to provide potential for muscular control improvement through augmented feedback. After all, the subject needs to act on the VR world to learn or should be given freedom to explore the training environment and arrive at an appropriate solution rather than be guided [19].

The maximal torque task (TASK 1) employed in our study consisted of a VR cylinder (Fig. 2A) extending up and down according to the assessed joint torque. The larger the extension or flexion torque was, the higher the cylinder extended and pushed the top red button. The red button stayed at the position, marking the maximal torque achieved and presented the goal, an issue for the subject to improve in further attempts. The
generated joint torque was measured with the built-in sensor in
the shaft of the dynamometer during isometric action [20] and
the maximal achieved torque was considered in maximal torque
limits in motor control VR task.

Figure 2. (A) The VR TASK 1 is intended for maximal joint torque
assessment, in which the subject needs to push the top red
button as high as possible. (B) The motor control task TASK
2 requires the subject to apply adequate extension/flexion
knee joint torque in order to move the VR object (bee) up
and down while moving over time through the VR office.
The ideally expected trajectory (red line) hitting all targets
(flowers) would be equal to the gait knee joint normative.

The motor control VR task (TASK 2) was designed as a
game in VR environment, where the vertical position of the VR
object was controlled through the generated knee joint torque,
while the object moved in horizontal direction in the virtual
environment over a designated time. If the subject generated
eknee extension joint torque, the VR object consequently moved
upward and when flexion joint torque, the VR object moved
downward. The exact vertical position of the VR object was
linearly related to the knee joint torque value. The total flying
time from start till the end of the VR environment was
considered as “gait cycle” (GC) time, set up by the therapist and
representing the task execution speed (Fig. 2B). The task
demanded from the subject hitting as many targets as possible.
The targets were presented as flowers placed around the virtual
office and being visited by a virtual bee, the VR object that was
associated with the subject’s action. The targets were positioned
in the VR environment in a way that the generated joint torque
trajectory would have been equal to the torque reference value
of the knee extensors [20] during gait, if the subject succeeded
to hit all the targets. The target was considered hit when the
generated torque was within the selected limits. The selected
limits influenced the task execution difficulty and thus defined
the difficulty levels. For level A, the torque variation could be
within 30% (± 15%) of the nominal torque, required to hit the
target, meaning that large tolerance made the task easy. For level
B, the tolerance limit was 10% (± 10%) of the nominal torque,
required to hit the target.

2.4 Protocol

The subject was seated on the Biodex reclining chair. Stabilization of the subject was achieved by placing velcro
straps across the chest, around the waist, just above the right
knee and just above the right ankle, which secured the right
lower leg to the input shaft of the dynamometer. The
dynamometer lever was set to 45° flexion due to mechanical stress [21] and the dynamometer operated in isometric mode
[20]. In addition, we visually aligned the estimated transverse rotational axis of the dynamometer. The surface EMG
electrodes were placed on the right lower extremity’s quadriceps muscle (rectus femoris). We repeated the entire test
procedure for the subject over 3 consecutive days at approximately the same time of the day to limit the extent of
possible diurnal variation. Each day, the VR task for maximal joint torque assessment (TASK 1) was performed; 3 times for
knee flexion and 3 times for knee extension. The protocol proceeded with the VR task for selective motor control training
(TASK 2). During the task execution, the surface EMG of quadriceps muscles was assessed. On the first day, a slow
(GC = 15 s) task speed was selected for each difficulty level, on
the second day, the task was performed also with the speed
increased for 50% (GC = 10 s), and on the third consecutive
day, for an additional 100% (GC = 5 s), in total 3 times faster
than the task execution speed at the beginning.

2.5 Data analysis

The generated knee joint torques, normalized on gait cycle,
were analyzed for each day individually to identify the
possible improvement in selective joint torque control.
Additionally, qualitative comparison to the reference torque
values (neurologically intact subjects [20, 22]), and reference
surface EMG of the quadriceps muscle group were checked.

A statistical analysis (SPSS v15, SPSS, Inc., Chicago, IL,
USA) of the impact of targets was performed to verify whether
the tracking of the targeted reference had improved. For each
target, the mean value and the standard deviation (SD) of
targets’ hits were calculated for each task execution speed as
well as the overall hit score statistics. The statistical significance
of the improvement (the difference between the target hits from
day-to-day) was also checked using statistical t-test. Finally also
the impact of difficulty level on target hits was examined.

3. Results

The results of the TASK 1 showed a day-to-day increase
in average maximal knee extension joint torque generation in
isometric conditions: day 1 = 12.3 Nm (SD 1.1), day 2 =
14.1 Nm (SD 2.3) and day 3 = 17.7 Nm (SD 1.2). The average
for knee flexion joint torque: day 1 = 15.3 Nm (SD 2.1), day
2 = 24.1 Nm (SD 3.1) and day 3 = 23.5 Nm (SD 2.1).

The normalized time course of the generated joint torque
showed high oscillations on the first day of the training session
TASK 2 (Fig. 3, upper panel). The subject was also trying to
correct his action by rapid flexion-extension movement,
especially when trying to hit the 2nd target. The action resulted
The assessed knee joint torque shows oscillations in the range (e.g. target no. 2) where high torque was required on the first day of training. The knee joint torque control has evidently improved as the subject was capable of target tracking almost without any oscillations at the end of the third day of training. Targets are marked with a triangle.

In oscillations at the moment where action was required, i.e. between 10% and 30% of the GC. The GC was 15 s and treated as very slow action.

On the second day of training (Fig. 3, middle panel) the subject showed more precise control of generated joint torque, and improved tracking resulted in hitting the target no. 2, also with higher task execution speed (GC = 10 s).

The lower panel of Fig. 3 shows that the oscillations caused by the quick knee extension/flexion torque had disappeared and the subject managed to control the joint torque as requested by the task. The bold line in Fig. 3 shows the mean value joint torque assessed each day for specific task execution speed and task difficulty level A.

The data assessed on three consecutive days were contrasted (Fig. 4) to the gait normative [23], the torque generated in the knee joint during neurologically intact persons’ gait with standard deviation. The joint torque generated on the third day of training, when the task execution speed was high (GC = 5 s), coincided with the normative, and on average, most of the task targets were hit. On the first training day, the subject could not manage to generate enough peak joint torque to hit target 2 due to the torque oscillations present. But on average, the subject had minor or no problems with hitting the targets, which did not require high joint torque.

The lower panel of Fig. 4 presents the quadriceps muscle group action. The subject generated higher and more expressed joint torque at highest task execution speed, which was only possible with well-controlled muscle activity, demonstrating smoother and more powerful surface EMG response. Between 7% and 20% of GC, one may notice that the recorded surface EMG showed multiple actions of the quadriceps muscle group according to the joint flexion/extension at the beginning of the training with speed 1.

Figure 4. The upper panel shows a stabilized, more powerful and targeted knee joint torque in the range of target no. 2 on the third training day, when also the task execution speed was higher (GC = 5 s). The knee joint torque, contrasted to the gait normative, also demonstrated better agreement after the training. Targets are marked with a triangle. The lower panel (surface EMG of the quadriceps muscle group) confirms better and more targeted muscle activity.
Table 1 demonstrates the hit statistics for each target separately for each training day (task execution speed) for difficulty level A.

<table>
<thead>
<tr>
<th>Target</th>
<th>HITS (%) (SD) Day</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>79.3 (16.4)</td>
<td>85.8 (9.2)*</td>
<td>84.5 (13.7)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>47.3 (13.7)</td>
<td>50.1 (33.2)</td>
<td>75.9 (24.0)*</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>84.0 (26.1)</td>
<td>96.9 (7.4)*</td>
<td>99.5 (0.5)*</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>70.0 (44.7)</td>
<td>89.4 (25.8)</td>
<td>80.9 (22.3)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>86.0 (13.4)</td>
<td>93.9 (14.9)*</td>
<td>100 (0)*</td>
<td></td>
</tr>
<tr>
<td>ALL</td>
<td>73.3 (30.5)</td>
<td>83.4 (20.7)</td>
<td>88.3 (15.9)*</td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.05, statistically significant differences between columns (target 1: 1-2, target 2: 1-3, 2-3, target 3: all, target 4: none, target 5: all, ALL targets: 1-3).

Results shown in Fig. 5 indicate the gradual increase of each target’s hits over all task difficulty levels; target 1 (76--+86%), target 2 (41--+50%), target 3 (79--+88%), target 4 (67--+88%) and target 5 (85--+98%). Even at intermediate task execution speed 2 (GC = 10 s), the target hits’ increase was evident. The only decrease (90.5--+88.0%) took place at the target 3 from day 2 to day 3, but was considered insignificant (p > 0.05). The target 2, which required the highest peak torque generation, demonstrated statistically significant (41.2--+50.0%, p < 0.05) target hit increase between the first and the last session.

![Figure 5. The VR target hit rate has increased for all targets (except for target no. 3 from day/speed 2 to day/speed 3) in 3 consecutive training days regardless of the task difficulty level.](image)

The overall hit statistics (all levels, all targets) also demonstrated an increase in mean hit score. On the first day (speed 1), the mean hit score was 70.0% (SD 17.3), on second day (speed 2), 77.8% (SD 19.2), and on the third day (speed 3), 82.4% (SD 18.5). The increase of the hit score from day 1 to day 3 was also statistically significant (p < 0.05).

4. Discussion

The results of a previous study [21] in neurologically intact individuals demonstrated that familiarization with the VR task resulted in increased efficiency (more target hits and higher task execution speed for selected difficulty level) during position-controlled dynamometer based on knee goniogram. A similar, but isometric approach has been applied in the current study’s CP subject in order to test whether the methodology is also feasible in children with CP and to investigate the impact of VR-supported dynamometer training on motor control behavior. The participating child had major difficulties with selective motor control and clinically identified contracture deformity hindering the knee joint movement. This resulted in muscle co-contraction, simultaneous hip flexion, knee extension and ankle dorsiflexion and consequently insufficient knee joint torque generation, which was required to hit the target, especially target no. 2. The subject was highly motivated and therefore push-pulled his lower extremity to finally reach the desired torque level, but unfortunately, the task was time-related and the target remained missed. Such action was recorded at the beginning of the training between 5% and 25% of the gait cycle (Fig. 3, day 1). Later on, gradually with practice, including verbal instructions to extend the knee joint only, the knee joint torque became more stable (Fig. 3, day 2); on day 3 even without any torque oscillations and hitting almost all targets (Fig. 3, day 3). Furthermore, each day of the training session, the task execution speed increased according to the protocol, but the VR-motivated subject still managed to control the knee joint torque within expected limits. This may also lead to the conclusion that higher task execution speed made the task easier. However, the higher task speed disabled the subject to perform multiple trials to hit the same target due to the shorter time available, but in order to hit the target and immediately stabilize the joint torque, an improvement of the selective motor control at the participating child was most likely essential. The mean knee joint torque values that were compared to the gait normative [21] also indicate better torque control and demonstrated higher knee torque output. The amplitude of the knee extensor surface EMG may confirm such action, especially if it is considered that the consecutive concentric/eccentric muscle action can be exhausting (Fig. 4, between 5 and 15% GC) [23]. Additionally, from day to day, the subject also generated higher maximal knee flexion/extension torque. We may suggest that it was due to muscle strengthening or more selective muscle control resulting in more efficient knee joint torque generation.

For the participating subject, the motivation to “win the game” was rather high priority. The subject’s effort to “win” explains the joint torque oscillations when trying to hit target no. 2. Besides the fact that the VR game presented a motivation for the subject, the training progress was focused on immediate action, which may be of great importance [19] and resulted in increase of target hits and the subject’s performance. The rising trend was positive, and the score improvement at the end of the training session demonstrated significant progress and also resulted in the subject’s satisfaction. Within the training sessions, also the task difficulty level was controlled, resulting in similar progress in target hit score. However, it should be considered that the subject’s motivation level was rather high and most likely contributed to the fact that the subject has gradually mastered the task. Nevertheless, when the child with CP achieved the same score several times in the row, the difficulty level or the game changed to keep up the subjects’ motivation. If the
achieved score was too low, the subject would have sooner or later given up, and if it was too high, we needed to offer additional levels. Until there is an issue for a child to “win”, he/she would be motivated. We may roughly estimate that with the proposed set of virtual tasks, a motivation could be preserved for approximately three weeks depending on the subject’s cognitive capabilities.

One of the main findings of our study is that the task difficulty level had no direct impact on joint torque and consequently on selective motor control improvement, if we consider that the same joint torque value may hit the target at the easy while misses at the difficult level. On the basis of our findings, we suggest that the proposed method can improve selective joint torque control under the supervised conditions and thus justify further clinical research.

5. Conclusions

In conclusion, we need to emphasize that for the participating child, suffering impaired motor control, the game presented a considerable challenge. The therapeutic goal of the game enabled the participating subject to learn how to control the dynamics of his motor system. Also, the importance of motivation and game attractiveness were considered [19]. The proposed feedback with VR target-oriented tasks has been demonstrated in a single-subject case study and may possibly present a powerful rehabilitation and assessment tool as it includes elements of increased motivation to attract the subject to the level that is at higher task execution speed, leading to gradual subconscious muscle action. As the action requires specific joint torque generation, it may result in improved dynamics of the motor control. The dynamics of the individual’s motor control is besides the muscle strength crucial for gait. Both items should be considered equally important in early treatment of cerebral palsy [24]. However, follow-up test and more extensive studies within a larger group of subjects are required to provide evidence that such gains of selective motor control are long-term and can be transferred outside the training context. Nevertheless, virtual technology as a rehabilitation tool should be considered as a step toward a future rehabilitation, where objective, repeatable task can be executed in remote environment, clinical or home and supervised with a limited number of clinical professionals [25].

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References