Development of an augmented treadmill for the rehabilitation of children with cerebral palsy: pilot perspectives from young healthy adult users

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ABSTRACT
A Real-time Treadmill Speed Control Algorithm (RTSCA) has been developed for gait rehabilitation of children with cerebral palsy (CP). The objective of the work described in this paper was to investigate the feasibility of the RTSCA prior to use by children with CP. Thirteen healthy subjects aged between 19 and 25 were recruited to walk on the treadmill using conventional speed buttons without the virtual reality (VR) environment, and the RTSCA with and without VR. The participants were asked to undertake three treadmill tests and to complete a questionnaire to provide feedback on the control of the treadmill. The descriptive results show that for 10 participants changing walking speed from stationary when using the RTSCA was similar or more comfortable to using conventional treadmill speed control buttons. For those who found it less comfortable the core issue was insufficient time to practise with the system. All the participants were satisfied with the safety and the performance of the RTSCA when incorporated into the VR scenario. A Wilcoxon test was conducted to examine whether there was a significant difference between walking speeds on the treadmill when using the conventional speed buttons and the RTSCA. The results showed that participants walked at significantly higher speeds when using the RTSCA. This may suggest that they walked more naturally or confidently on the treadmill when using the RTSCA as compared to the use of conventional treadmill speed control buttons.

1. INTRODUCTION
Cerebral Palsy (CP) refers to a set of disorders that can affect the progress of movement and posture, resulting in a limitation of activity [Gage, 1991]. The mobility of children with CP is normally better if the management of CP is provided effectively. Management focuses on using suitable combinations of interventions often through a multidisciplinary team. An important element of this management is gait (walking) rehabilitation often provided under the guidance of physiotherapists. However, staffing and clinical space allocation can limit the number of gait rehabilitation sessions that can be provided. In addition, some patients can find it difficult to maintain an appropriate level of motivation, particularly when sessions are undertaken in unrealistic environments or conditions.

Treadmill training is considered as a likely method to address some of these limitations. The potential of rehabilitation based treadmill training for children with CP has been recognised by previous research [Lancioni et al., 2009, Zwicker and Mayson, 2010]. The development of treadmill training is based on the motor learning theory which suggests that repetitive practise of the skills that need to be developed is important in re-learning those skills [Lancioni et al., 2009, Zwicker and Mayson, 2010]. Motivation on the part of the child, however, remains an issue [Lancioni et al., 2009]. The inclusion of a virtual reality (VR) environment into training which can then become, for instance, a structured ‘game’ that the child can become immersed in, is a possible approach to engaging children who might otherwise lack the motivation needed to complete a prescribed rehabilitation programme.

VR can be defined as an approach that allows users to interact with a computer simulated three-dimensional (3D) environment [Burdea and Coiffet, 2003]. It has been used in medical applications such as
rehabilitation and health care training. VR has been shown to facilitate rehabilitation sessions in a safe environment which then encourages patients to engage their sessions with higher attention [Rizzo and Kim, 2005, Rizzo et al., 2004]. The literature suggests that VR based gait rehabilitation for post stroke survivors can be more effective than conventional (over-ground) and treadmill based rehabilitation [Deutsch and Mirelman, 2007]. For children with CP, VR can help to increase self-confidence and motivation, resulting in improvements in upper extremity function [Parsons et al., 2009, Sandlund et al, 2011, Snider et al., 2010]. Recent literature also shows the potential for the use of games during lower extremity rehabilitation [Kott et al., 2009, Parsons et al., 2009, Snider et al., 2010]. However, further work is required in this area.

When using a treadmill, one of the issues with immersion is speed control, which conventionally is achieved by using buttons or controls on the treadmill. A powered but self-paced treadmill could be used to improve immersion; the treadmill speed responding to the speeding up and slowing down of the user, but without the need to use speed control buttons. The literature shows different techniques used in order to implement a general locomotion interface in a VR and/or for other purposes [Christensen et al., 2000, Lichtenstein et al., 2007, Manurung et al., 2010, Minetti et al., 2003, Souman et al., 2010, Von Zitzewitz et al., 2007]. A feedback-controlled treadmill locomotion interface was implemented based on a proportional - integral - derivative (PID) controller, with the difference between intended position and that from sensors attached to the user as input, and investigated by Lichtenstein et al [2007] and Minetti et al [2003]. The slow response of the treadmill to user movement on the treadmill was reported as one limitation in the study conducted by Minetti et al [2003]. In both studies, the PID control algorithm used to calculate treadmill speed is designed to maintain the user’s walking at a certain preset position on the treadmill. Due to the limited ability to change walking speed with this approach, users may not feel that they can walk naturally at a range of speeds on the treadmill. Christensen et al [2000] and Von Zitzewitz et al [2007] adapted the treadmill speed based on the force applied through a cable attached to a mechanical tether on the back of the user; the force changing as the user moved forward or backward during their walking on the treadmill. A limitation of this approach is that the attached tether may interfere with focusing solely on the activity. To address this, Manurung et al [2010] adapted a speed control treadmill algorithm based on the use of a sonar sensor, which was placed on the user’s back. The sensor determines how far the user is on the treadmill from a predefined reference point, and this distance in used by the algorithm to determine the walking speed. The approach demonstrated in this study enabled users to adjust their walking speed on the treadmill successfully; however, an approach is required to increase level of immersion and clinical applications (e.g. biofeedback and 3D kinematic) that can be associated with augmented treadmill training. One approach to addressing these concerns could be the use of optical motion capture systems that rely on small light-weight markers that can be attached readily to the user’s body [Souman et al., 2010]. Such an approach can be used not only to control speed using a position based algorithm with a simple array of markers, but through use of more complex marker sets, determine the placement of body segments in space to enhance the immersion of users in a virtual world. For this reason a motion capture based Real-time Treadmill Speed Control Algorithm (RTSCA) was developed as part of the Surrey Virtual Rehabilitation System (SVRS) [Al-Amri et al., 2011].

Before evaluating the RTSCA with children with CP it was considered necessary to investigate its use in people with unimpairment ambulation. For convenience, a group of young healthy adults was selected. This paper presents their perspectives on the safety and performance of the RTSCA. The hypothesis was divided into three parts as follows:

- H1: participants would find walking on the treadmill when using the RTSCA to be at least comparable in comfort and safety to that when using conventional treadmill speed control buttons
- H2: participants would be unable to walk on the treadmill under the RTSCA successfully and efficiently to complete a walk across a virtual city requiring regular speed adjustment
- H3: walking speeds on the treadmill when using conventional treadmill speed buttons would not be significantly different to those with the RTSCA

2. METHOD

2.1 Real-time Treadmill Speed Control Algorithm

The RTSCA is based on an open loop PID controller algorithm implemented in the Vizard Virtual Reality software (version 3.18.0002, WorldViz LLC, USA). It enables users to start walking on a stationary treadmill (PPS WoodWay treadmill, WoodWay, Germany) and for the treadmill speed to respond to their movement. Users wear a pelvis reflective marker ‘cluster’ (see Figure 1) and two reflective markers on their feet, the latter to stop the treadmill if users step outside the treadmill belt. The Qualisys optical infrared tracking system (version 2.4.546, Qualisys AB, Sweden) is used to track marker positions. The software calculates the
longitudinal difference between the pelvis cluster origin and the treadmill origin point; this difference \( (x_c) \) is then used to compute the Calculated Treadmill Speed (CTS) as illustrated in equation 1. The CTS is sent to the treadmill through a RS232 serial connection.

\[
CTS(t) = k_p x_c(t) + k_d \left( x_c(t) - x_c(t-1) \right) + k_i \sum x_c(t) \tag{1}
\]

\( k_p, k_d, \) and \( k_i \) are the coefficients for the proportional, derivative, and integral terms, respectively that were calculated using the Ziegler–Nichols method [Xue et al., 2008].

![Figure 1](image)

**Figure 1.** A participant using the RTSCA. A: pelvis cluster – a sprung loaded frame with 3-point contact to calculate the origin of the pelvis segment; B: markers on feet; C: one of the eight motion capture cameras used.

The PID control algorithm was tuned in trial experiments with 5 volunteers during which the treadmill speed changed when different values of the PID coefficients were tested. As a result, the optimum coefficient values were chosen as those that enabled users to walk with stable treadmill speeds with a maximum fluctuation of approximately 0.015 m/s (considered to be not noticeable) which was based on the responses from the test volunteers, and with the flexibility to increase walking speed gradually from zero up to a maximum walking speed of 1.9 m/s. Figure 2 shows four trials from a test with one user with different values for the PID coefficients. In the first and fourth trials, the fluctuation was noticed and the user took longer to reach their normal walking speed. The second trial did not enable the user to maintain a comfortable walking speed without unacceptable fluctuations in speed. The third trial allowed the user to walk at what they considered their comfortable walking speed without noticeable fluctuation.

Safety is clearly an important issue and the RTSCA is designed to trigger a controlled emergency stop, such that the system decelerates the belt speed to zero (at approximately 5 m/s\(^2\)) if any of the following occur:

- The user’s pelvis obliquity, rotation, or tilt exceeds 25°
- The user steps outside the defined treadmill belt area, determined using the foot markers
- The connection between the treadmill and/or the marker detection system, and the controlling computer is interrupted
2.2 Research Participants

Ethical approval was granted by the University Ethics Committee. Criteria for inclusion in this investigation were: female or male; aged between 18 and 25 years; not involved in preliminary testing with the system; and able to answer ‘NO’ to all questions on a simple screening questionnaire (Table 1).

Table 1: Questions in the Screening Questionnaire.

<table>
<thead>
<tr>
<th>No.</th>
<th>Question</th>
<th>No.</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Have you any medical conditions that have affected your vision or walking ability in the past six months?</td>
<td>2.</td>
<td>Do you have photosensitive epilepsy?</td>
</tr>
<tr>
<td>3.</td>
<td>Do you experience dizziness during or after walking continuously for 10 minutes?</td>
<td>4.</td>
<td>Do you ever experience headache as a result of watching/using a TV or PC for 30 minutes?</td>
</tr>
<tr>
<td>5.</td>
<td>Are you unable to perform walking exercise for 10 minutes without taking a rest?</td>
<td>6.</td>
<td>Do you ever experience dizziness as result of watching/using a TV or PC for 30 minutes?</td>
</tr>
<tr>
<td>7.</td>
<td>Do you have uncorrected problems with your vision?</td>
<td>8.</td>
<td>Do you ever experience nausea as a result of watching/using a TV or PC for 30 minutes?</td>
</tr>
</tbody>
</table>

2.3 Procedure

The investigation was conducted in the Gait Laboratory at the University of Surrey and divided into three tests. Prior to performing these tests, participants had the opportunity to practise using the treadmill, particularly for those unfamiliar with using one in the past. Test one was designed to determine the participants’ self selected slow, normal and fast comfortable walking speeds, when using the treadmill speed buttons without VR. In test two participants were asked to walk on the treadmill to reach self-controlled slow, normal and fast speeds using the RTSCA without VR. Both tests consisted of three trials; each was started with the participants standing at the origin point on the stationary treadmill. In the first trial of test one, the participants were asked to start walking on the treadmill until they felt they were walking at what they considered as their normal walking speed. The speed was monitored and they were asked to maintain...
that speed for a further 20 seconds. Participants were then asked to reduce their speed to zero gradually. In the second trial, they were asked to follow the same procedure, but to walk at what they considered to be their fast walking speed. For the third trial, the participants were asked to walk on the treadmill at a slow walking speed for 20 seconds. They were then asked to change the speed to what they considered to be their normal walking speed and to maintain that speed for a further 20 seconds. They were then asked to change the speed to what they considered to be their fast walking speed and to maintain it for a further 20 seconds. After that, they were asked to stop safely by reducing their speed gradually to zero. At the end of this test, the participants were asked to complete 7 closed-ended questions.

In test two and after checking the motion capture system tracked all the reflective markers, the participants were asked to walk forward slowly to the (self selected) target speed for each of the trials following the procedure outlined in test one. At the end of the third trial, the research participants were asked to complete 11 closed-ended questions. For the third test, the participants were asked to walk forward slowly to reach their preferred self-selected walking speed in order to walk across a virtual city within a certain time (65 seconds). When walking across the city, they were asked to adjust their walking speed in order to avoid colliding with a virtual ball that appeared at random intervals for 5 seconds. At the end of this test, the participants were asked to complete 3 closed-ended questions and an open-ended question.

2.4 Statistical Analysis

The investigation was based on responses to a questionnaire that had two components. The first comprised 18 closed-ended questions and an open-ended question on the overall experience of walking on the treadmill as detailed above. The second was based on additional three closed-ended questions and an open-ended question that focused on the overall performance of the RTSCA when integrated with the virtual 3D scenario. The descriptive analysis and subsequent findings were obtained by using Microsoft Excel 2007. The data obtained by the open-ended question and the discussion with the researcher were also used to support the descriptive results of the closed-ended questions. A Wilcoxon test was conducted to examine whether there was a significant difference between walking speeds on the treadmill when using the conventional treadmill speed buttons and the RTSCA. The Statistical Package for the Social Science (SPSS) software for Windows was used to perform this test.

3. RESULTS

Thirteen young healthy adults (8 males, and 5 females), aged from 19 to 25 years (mean age was 22.15 ± 2.04) participated. The results from their responses are presented below.

3.1 Perspectives on the Treadmill when using Treadmill Speed Buttons

Seven closed-ended questions were asked to determine the perspectives of walking on the treadmill using conventional speed buttons. The responses are summarised in Figure 3. The results show that the majority of the 13 participants (9 and 11 respectively) found the ability and ease of accelerating from stationary on the treadmill at least as comparable to accelerating during normal over-ground walking. For the ability and ease to change from one constant speed to another, 11 and 10 participants respectively responded that it was at least comparable to what they do during their normal over-ground walking. None of the participants found the ability to maintain their walking speeds on the treadmill was worse than over-ground walking. For comfort in maintaining speed, 10 of them found it comparable to or better than over-ground walking. Nine participants found the comfort of stopping on the treadmill to be comparable to or better than what they do during over-ground walking.

3.2 Perspectives on the Treadmill when using the RSCA

The perspectives on the experience of walking on the treadmill using the RTSCA were determined through the participants’ responses to 9 closed-ended questions (Figure 4). In assessing their ability and ease to accelerate from stationary, 9 and 8 participants respectively found that the RTSCA enabled them to do so as or better to what they do during over-ground walking, respectively. Although 3 participants responded that the ease of changing from stationary to normal walking speed worse than over-ground walking, only one participant was unable to maintain it. The perspectives were fairly similar on the ability and ease of using the RTSCA for their slow walking speed. For ease of changing from stationary to fast walking speed, 8 participants found it comparable or better than over-ground walking. In terms of ability to maintain their fastest walking speed, 8 participants responded that it was worse than over-ground walking. Ten participants felt that they stopped comfortably as and better than what they do naturally.
In addition, a specific question was asked whether the participants walked at what they considered to be their fastest walking speed; the results show that the majority of the 13 participants (10) felt that they did not do this.

**Figure 3.** Responses to questions on the participants’ walking experience on the treadmill when using conventional speed buttons. Number in a legend refers to number of responses.

**Figure 4.** Responses to questions on the participants’ walking experience on the treadmill when using RTSCA. Number in a legend refers to number of responses.
In order to explore perspectives on walking on the treadmill when using its speed control algorithm compared to its conventional speed buttons, two general questions were asked (see Figure 5). Ten participants reported that their ability to maintain and ease to change walking speeds from stationary when using the RTSCA was better and comparable to the use of conventional speed buttons.

![Figure 5](image1.png)

**Figure 5.** Responses to general questions on the participants’ walking experience on the treadmill when using the RTSCA compared to the use of its conventional speed buttons. Number in a legend refers to number of responses.

### 3.3 Perspectives on the Treadmill when using the RTSCA with Virtual City

To explore the performance of the RTSCA when it was incorporated with a VR environment, three closed-ended questions were asked. As can be seen in Figure 6, all the participants were content with the interaction between the virtual environment (virtual city) and the treadmill when using the RTSCA. In terms of how easy it was to use the RTSCA to change between walking speed in order to walk across the virtual city, 11 participants agreed or strongly agreed. Nine participants considered that incorporating the virtual city with the treadmill encouraged them to use the RTSCA. For the open-ended question asking participants for any further comments, 11 participants responded. All of these responses were very positive, apart from a general comment of not being able to walk at fastest possible speed with the RTSCA. For example, a participant stated that “I felt that I could walk faster but the system did not give more speed” another participant also stated that “I did not reach my fast speed at the end of the treadmill”. Comments also suggested that a few participants felt that they did not practise enough with the RTSCA before the testing. A participant stated that “I think I was not right when I said that I got enough practising of how to use the proposed approach, however, the experience of using this approach was really great”.

![Figure 6](image2.png)

**Figure 6.** Responses to questions on crossing the virtual city experience when using the RTSCA. Number in a legend refers to number of responses.
3.4 Treadmill Speeds

Table 2 shows statistical results for walking speeds with the RTSCA and speed buttons. The mean self-selected normal walking speed of participants increased by 0.21 m/s when using RTSCA compared to treadmill speed control buttons. Similarly, the mean self-selected slow walking speed increased by 0.18 m/s with the RTSCA. In contrast, the mean self-selected fast walking speed only differed by 0.01 m/s. The mean fluctuation for each speed when using the RTSCA was less than 0.015 m/s. A Wilcoxon signed-rank test was performed to examine the hypothesis (H3), with set significance level at p≤0.05.

Table 2. Analysis of walking speeds average under the RTSCA and the treadmill speed buttons. St dev: Standard Deviation.

<table>
<thead>
<tr>
<th>Speed Buttons</th>
<th>RTSCA</th>
<th>Fluctuation</th>
<th>Wilcoxon test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (m/s)</td>
<td>St dev (m/s)</td>
<td>Mean (m/s)</td>
</tr>
<tr>
<td>Normal walking speed</td>
<td>1.06</td>
<td>0.15</td>
<td>1.27</td>
</tr>
<tr>
<td>Slow walking speed</td>
<td>0.76</td>
<td>0.10</td>
<td>0.94</td>
</tr>
<tr>
<td>Fast walking speed</td>
<td>1.74</td>
<td>0.11</td>
<td>1.75</td>
</tr>
</tbody>
</table>

4. DISCUSSION AND CONCLUSIONS

This paper discussed the overall performance of the proposed augmented speed control treadmill technique as perceived by healthy young adults. The majority of the participants found walking on the treadmill when using the RTSCA similar or more comfortable to using the conventional speed buttons. One key element of this investigation was to observe the safety of using the RTSCA. During the experiment, there were no accident or negative comments about the safety of RTSCA with and without VR. As part of its safety and performance, interestingly, the participants did not notice any possible delay between their walking speeds on the treadmill and the VR speed, which suggests that the RTSCA enabled participants to walk on the treadmill at different speeds smoothly and without noticeable changes in the treadmill speed. The results outlined in this paper indicate that the majority of the participants were content from VR environment and the RTSCA when incorporated with that scenario. Together, these results suggest that the first hypothesis can be accepted and the second rejected. Statistical results illustrate the standard deviation of all speeds under the RTSCA were lower or equal to those under the speed buttons. This indicates that the RTSCA enabled the participants to walk with consistent speeds at least as comparable to those when using the speed buttons.

The results of the statistical test indicate that the H3 has been rejected for the normal and slow walking speeds (p value<0.05), but it has been accepted for the fast walking speed (p value>0.05). Feedback provided by participants on the ability to walk at the fast speed was an interesting response given that the fast speed reached by all participants when using the RTSCA was almost equal to their fast walking speed that was recorded during their use of the treadmill speed buttons. A similar conclusion to this were recorded by Lichtenstein et al [2007]. In their study, they reported that subjects showed slower speeds on a treadmill when using a self-propelled (conventional) mode compared to the use of a controlled mode. A limitation of this study is that the walking speeds of the participants in over-ground were not recorded. Therefore, future research should consider this in order to ensure that the RTSCA does not prevent users from walking at their natural speeds.

Whilst positive feedback on the use of the RTSCA was provided by participants, there were comments about insufficient practise prior to using the RTSCA. This will be addressed in future work. For the purpose of our research, the results of this pilot investigation have encouraged us to proceed to a clinical study in which children with CP will walk on the treadmill following the procedure outlined in this paper. Ongoing research will also explore the replacement of the motion capture system by a low-cost markerless system, e.g. Microsoft Kinect for the Xbox 360, allowing the ideas discussed to be more easily implemented in the clinical setting.
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5. REFERENCES


