Mobility following TBI: relationships with ankle joint power generation and motor skill level.

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Abstract

Reduced balance, spasticity, contractures, muscle weakness and motor skill levels may all contribute to mobility limitations following TBI, yet the key physical impairments that contribute to mobility limitations remain unclear. The aim of this study was to determine which physical impairments best predict mobility performance after a period of six months of rehabilitation. Participants with TBI were selected if they were receiving therapy for mobility limitations but were able to walk without physical assistance. The clinical assessment included measures of balance, spasticity and contracture and 3DGA was used to quantify joint power generation and motor skill level on 31 adults with severe TBI. Mobility outcome was quantified with the high-level mobility assessment tool (HiMAT). Two variables, ankle joint power generation during the push-off phase of gait and motor skill level, explained 66.5% of the variability in mobility outcome. Balance, strength and mobility performance all improved significantly over the six months of rehabilitation. Only two participants had contractures which impacted on mobility. Balance disorders were prevalent and improved with rehabilitation, yet contributed to only a limited extent to the level of recovery in mobility. Ankle joint power generation at push-off was the strongest predictor of mobility outcome after six months of rehabilitation in ambulant people with TBI.
1. Introduction

Traumatic brain injury (TBI) is the main cause of death and disability in people aged 18-45 years.\(^1\) Surprisingly little is known about the impact of TBI on mobility despite the frequency of mobility limitations associated with moderate to severe injuries.\(^2\) Moreover, little is known about the nature of gait disorders following TBI,\(^3\) and the contribution of physical impairments to mobility limitations. Whilst gait, or walking, is the primary means for which people move about, mobility is a broader term used to encompass a range of activities from getting in and out of bed to climbing stairs and running.

The complex, variable and diverse clinical presentation which may occur following moderate to severe TBI warrants identification of the key physical impairments associated with improved mobility outcomes. This may, in turn, assist clinicians to design targeted intervention strategies. Substantial gains in mobility have been achieved during the early\(^4-6\) and later\(^7\) stages of rehabilitation. Similar gains in physical impairments have also been achieved.\(^2, 4, 6\) Several studies have identified predictors for independent mobility,\(^8, 9\) or identified variables which are strongly correlated with better mobility outcomes.\(^6, 10, 11\) These predictors include factors such as age at time of injury,\(^8\) severity of brain injury,\(^9, 12\) lower extremity fractures,\(^11, 13\) spasticity,\(^13\) standing balance\(^6, 10\) coordination\(^11\) and lower limb strength.\(^6, 11\) Although these findings may guide clinical decision making, to the best of our knowledge, no studies have included all the major contributing physical impairments when attempting to identify the best predictors of mobility outcomes.
The major physical impairments that may potentially contribute to mobility limitations following TBI include balance, spasticity, contracture, muscle strength and motor skill level. These impairments are prevalent following moderate to severe TBI, but the extent to which each of these impairments influences mobility performance may vary considerably. For example, poor balance and postural control was thought to result in reduced walking speeds in independently ambulant patients. In contrast to this premise, recent research has found that although reduced ability to balance is prevalent, it does not restrict many independently ambulant people with TBI from walking at fast gait speeds. Reduced mobility performance was associated with an inability to generate adequate ankle joint power generation during push-off at self-selected speeds, suggesting that weakness of distal muscle groups in the lower-limb may play a role. While there is evidence to support the impact of each physical impairment on gait performance, in the presence of multiple physical impairments, all potential contributing factors need to be evaluated together in order to determine which impairments are the strongest predictors of mobility outcomes following TBI. Therefore, the primary aim of this study was to determine which physical impairments best predict mobility outcome, as measured by the high-level mobility assessment tool (HiMAT), over a six month period of rehabilitation following TBI. A secondary aim was to identify the extent to which physical impairments and mobility change over a six month period of rehabilitation. The six month time frame was selected due to the slow recovery rate of many adults with severe TBI.

2. Methods

2.1 Participants
This project was approved by Epworth Hospital’s HREC (study number 34006), and the University of Melbourne (Ethics ID: 060496.1).

Participants with TBI currently attending physiotherapy for mobility limitations at Epworth Hospital were invited to participate in this project. The inclusion criteria were patients who:

(a) had sustained a TBI; (b) were attending physiotherapy for mobility limitations; (c) were able to walk without assistance of a therapist or gait assistive device over a distance of 20 m; and (d) provided informed consent. Exclusion criteria were patients who: (a) were unwilling or unable to provide informed consent; (b) had pre-existing central nervous system disorders and; (c) had severe cognitive (unable to follow two-stage commands) or behavioral problems that prevented patients’ ability to comply with the assessment. All subjects (see Table 1) who were invited to participate consented to do so. As this was an observational study, no attempt was made to influence or measure the frequency or type of therapy provided to participants.

2.2 Procedures

Participants were required to undergo a routine clinical assessment of physical impairments and three-dimensional quantitative gait analysis (3DGA) in order to quantify the variables of interest. The five measures of physical impairment were balance, spasticity, contracture, muscle strength and motor skill. All measures were repeated after a period of six months (+/- 14 days).

Clinical Assessment

Balance was measured using a clinical test of single limb support (SLS) duration. This test was chosen due to its potential ability to discriminate the performance of more able participants. An additional reason for selecting this test was that it is ‘static’, i.e. it does not require participants to move around. Since people with TBI may experience problems
bilateral, both legs were tested for each participant. Static balance was measured via SLS for each leg with eyes open (EO) and eyes closed (EC), up to a maximum of 30 seconds. Participants were instructed to stand in SLS with their hands on their hips (where possible) and not to let their legs touch. The trial ceased if the participant moved the stance foot, put the non-stance foot down, touched his or her legs together, or lost hand contact with their hips for more than a brief moment. The trial also ceased for the EC condition if the participants opened their eyes. Participants performed three trials of each condition. The average time for the three trials for each condition was then calculated. The average times for each of the four conditions (left and right legs, EO and EC) were summed to create a total SLS score (maximum total score = 120 seconds) to represent static balance performance for both legs. Previous results have indicated that a summed composite score is a better measure of standing balance than individual scores. In order to quantify the impact of spasticity on mobility performance, all the main muscle groups which are commonly affected by spasticity were assessed using the Tardieu scale for both lower limbs. These muscle groups were hip flexors, extensors and adductors, knee flexors and extensors, and ankle plantarflexors (soleus and gastrocnemius scored separately) and invertors. This scale was chosen due to its demonstrated sensitivity and reliability. The Tardieu scale scores spasticity from 0-4 with higher scores representing a greater severity of spasticity. To the best of our knowledge, no information is available indicating that spasticity affecting certain muscles may have a greater influence on mobility than other muscle groups. In order to determine the influence of spasticity on mobility, Tardieu scores for each muscle were summed to generate a total ‘spasticity score’ for each participant. The maximum potential score for each leg was 32, resulting in a total possible score of 64. Joint and muscle range of motion (ROM) was assessed to determine the impact of contracture on mobility. Passive ROM was measured for the hip, knee and ankle joints in all three planes.
of motion with a goniometer. Hand-held goniometry is a very common and accurate method for measuring joint ROM. In addition to joint ROM, hamstring, gastrocnemius, rectus femoris and iliopsoas length were measured. Hamstring length was measured in supine with a straight leg raise – the angle at the hip was recorded. Calf length was measured in supine with a straight knee – the angle at the ankle was recorded. Rectus femoris length was measured with a prone knee bend - the angle at the knee was recorded. Iliopsoas length was measured in prone with a straight leg raise – the angle at the hip was recorded.

Three-dimensional quantitative gait analysis

To generate objective information related to muscle strength and motor skill, all participants completed a 3DGA. Ground reaction force data were collected at 1080 Hz using three AMTI force-plates mounted in the floor on the laboratory. Kinematic data were acquired using a 3D motion analysis system (Vicon 512, Oxford Metrics, Oxford, England) with eight high-resolution cameras sampling at a rate of 120 Hz. Kinematic and kinetic calculations were performed using Bodybuilder software. Thirty-eight small (14mm diameter) passive reflective markers were mounted on the skin at specific locations on the pelvis and both lower limbs. Three markers were also placed on the trunk overlying the spinous processes of T2 and T10 as well as the sternal notch. Participants initially performed a standing calibration trial to define joint centre locations and anatomical coordinate systems. All anatomical coordinate systems were defined as per a previously described approach, except that the location of the hip joint centre in the current study was predicted using the method of Harrington et al. (2007). Participants with TBI performed walking trials over a 12 m walkway whilst data were collected at their self-selected walking speed. Spatio-temporal,
kinematic and kinetic data for five trials were captured for each lower limb to gain a representative sample of each participant’s gait pattern. Strength was quantified by measuring the peak ankle joint power generation during push off for the most affected leg. The most affected leg was nominated by the participants. Ankle joint power generation during push-off, quantified by 3DGA, is not a direct measure of muscle strength, yet it does represent a task-specific application of calf strength for gait. Ankle joint power generation during push off is the largest power generated in the gait cycle. Following TBI, compensatory strategies with proximal muscle groups are often used in the presence of reduced ankle joint power generation. Ankle joint power generation during push-off has also been shown to be strongly correlated with higher self-selected walking speeds in TBI. Therefore, only ankle joint power generation during push-off was selected for investigation as a predictor of mobility outcome. Clinical methods for measuring muscle strength include manual muscle testing and hand-held dynamometry, yet evidence suggests they may not be capable of providing accurate indications of muscle power. Isokinetic strength testing may be highly accurate, but it is expensive and primarily laboratory-based. This cohort of people with TBI was a sub-group from a larger study involving 3DGA. Although 3DGA involves expensive laboratory-based instrumentation, McGinley et al have shown in a prior study that accurate and reliable judgments regarding push-off can be made by clinicians using visual observation. The ability to make accurate, no-cost judgements of ankle joint power generation during push-off provides clinicians with a method for determining a patient’s ability to perform the most important power production event during the gait cycle. Motor skill performance refers to the ability to generate a purposeful, smooth and efficient movement. Motor skill for walking was assessed using the Gait Profile Score (GPS). The
GPS was selected because it is specific to the motor skill of walking and is the most accurate single index of gait performance.\textsuperscript{38, 39} The GPS was developed as a single index to measure the quality and normality of a patient’s walking pattern.\textsuperscript{38} Nine kinematic measures of pelvic, hip, knee and ankle movements, together with foot progression, are collated. The mean performance of five trials for each patient’s kinematic trace for each of the nine parameters was compared to the average values obtained from a sample of 10 healthy controls (HC).\textsuperscript{18} The difference between the participant’s trace and the mean of the HC sample was measured and summed into a representative GPS, with higher scores representing greater abnormality. A single representative GPS was derived from the average of the scores obtained for each leg.

**Mobility**

The few studies which have attempted to predict mobility outcome have tended to focus on independent ambulation and self-selected walking speed as the primary outcome.\textsuperscript{8–10} Although independent ambulation is a major aim of rehabilitation, many people with TBI have advanced mobility goals.\textsuperscript{7, 40} As a primary outcome for mobility, self-selected walking speed is susceptible to a ceiling effect whereby it is natural to progress into faster walking and running. Therefore, mobility performance was measured using the high-level mobility assessment tool (HiMAT).\textsuperscript{41} The HiMAT was selected as a clinical measure of mobility because it is more responsive to change and less susceptible to a ceiling effect for people with TBI who can walk independently of gait aids.\textsuperscript{41, 42} It measures walking under various conditions, stair use, running, skipping, hopping, and jumping. Higher scores indicate better performance (maximum score = 54). A four-point improvement over three months indicates significant improvement.\textsuperscript{42} Self-selected gait speed over a 10m walkway was also recorded as a point of reference of the participants in this study.
2.3 Statistical analysis

Preliminary analyses were conducted to ensure no violation of the assumptions of normality, linearity, multicollinearity and homoscedasticity. Standard multiple regression was used to determine to what extent measures of physical impairment predict mobility outcome. The five predictor variables were balance, spasticity, contracture, muscle strength and motor skill, and the dependent variable for mobility was the HiMAT. No post-hoc tests were planned or performed. Repeated measures $t$-test was used to determine which impairments changed over a 6 month period of rehabilitation. All analyses were performed using the SPSS (v19) software.

3. Results

This cohort of 31 people (see Table 1) were primarily young and male (n=23), representative of a sample of very severe TBI (27 participants had a length of post-traumatic amnesia > 28 days). No participants were lost to follow-up. Insert Table 1 about here.

In relation to muscle and joint contracture, very few participants had a restriction to ROM to an extent that was likely to have influenced mobility performance. No participants had restricted ROM at their hip, knee or ankle joints within the ROM required for normal walking or running\textsuperscript{33,43,44}. All participants had sufficient length in their hamstrings, rectus femoris and iliopsoas muscles. Two participants were unable to achieve plantargrade in supine lying when their calf was placed on stretch. Since only two participants had restrictions to muscle length, contracture was eliminated from the regression analysis.
Predictors of mobility

Standardized multiple regression was used to assess the ability of four measures of physical impairment (balance, spasticity, muscle power and motor skill) to predict mobility outcome at 6 months, which was on average 14.8 months post-injury. The total variance explained by the model as a whole was 66.5%, $F(4, 22) = 10.9, p < .001$. Only two variables, ankle joint power generation (beta = .48, $p < .01$) and GPS (beta = -.29, $p = .05$) were statistically significant in the final model.

Six-month follow-up

Six-month follow-up results demonstrated a significant improvement in mobility. The average improvement score of 14.5 points in 6 months was well above the minimal detectable change score for improvement on the HiMAT (four points in 3 months).

Statistically significant improvements were found in muscle strength (ankle joint power generation during push-off) and total balance scores (Table 2). Despite the improvement in total balance score, balance was not included in the regression model generated for predicting mobility outcome. Spasticity was prevalent in this cohort with 65% of participants recording a Tardieu score. No significant change was identified in spasticity scores at 6 month follow-up despite large gains in mobility performance. Similarly, no significant group change was detected in motor skill (GPS scores) at 6 month follow-up.

Discussion
The ability to generate ankle joint power during push-off was a strong predictor of mobility outcome for this cohort of ambulant people with severe TBI. Together with motor skill performance (as measured by the GPS), these physical impairments predicted 66.5% of the variability in mobility outcome at 6 month follow-up. Although improvements in standing balance occurred over the six-month period of rehabilitation, standing balance did not add to the model generated to predict mobility outcome. The inability to generate ankle joint power during push off, rather than postural instability and reduced standing balance, was previously identified as the primary reason for slow gait speeds following TBI\textsuperscript{18}. The results obtained in this study also supports previous data indicating that despite moderate correlations between mobility and standing balance, standing balance performance alone cannot be used to predict mobility outcome.\textsuperscript{24} This suggests that ankle joint power generation during push-off and motor skill are two key physical impairments to consider when retraining gait following TBI.

Slow self-selected walking speed has been widely reported following TBI.\textsuperscript{10, 18, 45, 46} Recent findings by Williams et al. (2010) indicate that ankle power generation at push-off is strongly related to higher self-selected walking speeds following TBI.\textsuperscript{18} The study by Williams et al. (2010) demonstrated that in order to walk at faster speeds, people with TBI preferentially increase their hip joint power generation due to limited ability to increase their ankle power generation. The findings in this current study indicate that improved mobility outcomes may be related to improved ankle power generation for people with TBI who are already ambulant. Improved ankle power generation during the recovery period following TBI may reduce the need for excessive hip power generation when walking faster or performing higher level mobility tasks such as running. Importantly, the dependent variable in this case was the HiMAT, and not self-selected walking speed, indicating ankle power generation is associated
with mobility outcomes beyond the fluctuations expected with gait speed. Further investigation of the most effective methods for improving ankle power generation during rehabilitation seems warranted in order to improve mobility outcomes following TBI. Gait Profile Scores remained stable even though significant improvements occurred in HiMAT scores and self-selected gait speeds. It may be possible that improvements to motor skill occurred which were not detected by GPS. Gait Profile Scores were calculated by comparing each participant’s trace to a HC sample walking at 1.04 m/s, a speed midway between the mean initial and follow-up TBI self-selected gait speeds. The speed at which a person walks directly impacts on joint ROM. Greater joint ROM is required as walking speed increases. Less joint ROM was required for walking for participants with TBI during the initial trials when compared to the HC sample that were walking at a relatively faster speed. Conversely, greater joint ROM was required for the TBI participants during the six month follow-up trials than the HC sample because they were walking at a faster speed. The GPS calculates the difference between a participant’s and HC’s kinematic trace in absolute terms, and can’t be normalised for gait speed. Therefore, a change from relatively less movement before, to relatively greater movement after, may result in no overall change to the GPS. Further investigation is required to determine whether motor skill performance, as measured by GPS, does improve during the course of rehabilitation, and the extent to which gait speed impacts on GPS.

Three-dimensional quantitative gait analysis was used in this study to generate surrogate measures of muscle strength and motor skill. In both instances, 3DGA was able to generate objective data to enter into a regression model to identify the predictor impairments. Now that two of the physical predictors for mobility outcome have been identified, it is possible for no-cost alternatives to be used in clinical practice for making accurate judgments of
muscle strength and motor skill. McGinley et al. (2003) have shown that accurate and reliable observations of push-off can be made by clinicians using visual observation, indicating that precise clinically-based judgments of ankle joint power generation during push-off can made with confidence. Further, when measuring mobility, judgments based on overall quality of movement are very highly correlated with quantitative performance, indicating clinician judgment of motor skill for mobility can be accurately determined. Visual observation is one of the most commonly used methods of gait assessment, so it is encouraging that accurate judgments of ankle joint power generation during push-off and motor skill of walking can be made in clinical practice.

The ability to balance in single limb support did improve significantly at follow-up, but did not add to the prediction of mobility performance. It appears that improved mobility outcome occurs in parallel to improvements in ability to balance rather than as a result of it. This finding supports our previous finding that despite strong correlations between total static balance scores and mobility performance, static tests of balance are only weak predictors of mobility performance following TBI. However, Sullivan (2007) found balance to be the strongest predictor of gait speed in a sample of 50 community dwelling people with stroke. The measure used to quantify balance was the Berg Balance Scale (BBS). The BBS was not selected for this study as it is susceptible to a ceiling effect in TBI. Although this TBI cohort had sustained severe injuries and had significant mobility limitations, the TBI self-selected gait speed (0.88 m/s) was higher than that reported by Sullivan (0.54 m/s for females and 0.67 m/s for males). It may be possible that balance is a key predictor of mobility performance in older people who are walking more slowly, but as recovery continues, other physical impairments such as strength and motor skill may become more important.
Prolonged bed rest, disuse and spasticity may all contribute to the development of contracture following TBI\textsuperscript{16,52-55} in some individuals. Despite most participants sustaining an extremely severe TBI, only two participants had a muscle or joint contracture large enough to impact on gait performance. The very low incidence of contracture is unexpected given that eleven participants had also sustained fractures to at least one lower limb, and the majority of participants experienced problems with spasticity. Although prevalent in this sample of people with very severe TBI, spasticity scores only marginally improved at follow-up. Despite the potential for spasticity to affect gait performance,\textsuperscript{52,54} large gains in mobility performance were obtained despite the prevalence of spasticity. Notwithstanding the prevalence and severity of the injuries sustained, it appears that the therapeutic interventions the participants were receiving had been effective in maintaining adequate joint and muscle ROM for walking. Contracture may be more prevalent in people with TBI who require assistance to walk or who are pre-ambulant.

**Limitations**

The clinical presentation of TBI may vary considerably across individuals, yet a basis for classifying into sub-groups such as ataxia or hemiparesis has not been established.\textsuperscript{3} It may be that predictors for mobility outcomes vary for different clinical sub-groups, and the findings in this study may only be applicable to with TBI who were able to walk without physical assistance. The predictors for walking in an acute non-ambulant TBI population may differ from the predictors identified in this study, and further predictors for mobility, such as vestibular disorders, may exist which were not investigated in this study. Moreover, as this was an observational study, clinical interventions were not prescribed or recorded.
comment can be made regarding the type, quality or quantity of the therapy the patients received during the six month period of rehabilitation. It may be possible that different mobility outcomes may have been obtained if the participants had received different therapeutic interventions.

Consideration also needs to be given towards the choice of measure for each variable in this study. Alternative methods may be used to quantify motor skill, strength, balance, spasticity and mobility. In each instance we have attempted to utilize the most accurate and relevant measure. For example, we selected a static test of balance which would best discriminate performance in this population, yet the chosen test requires participants to stay still. Alternative tests of dynamic balance were not selected in order to avoid contamination with the movements and mobility required for successful dynamic balance. Although the Tardieu scale is widely used in neurological populations, we are unaware of previous attempts to sum scores as we have in this study. Spasticity may affect a large number of muscles, and a wide combination of muscles following TBI, so it would seem appropriate to include all major muscle groups of the lower limb. No evidence exists to suggest that spasticity to any particular muscle group has a greater influence on gait performance to justify the selection of a single muscle group for testing. Further examination of the validity of a summed spasticity score is required, but at this stage we are unaware of any alternative methods for quantifying the effect of lower limb spasticity on gait.

Due to limitations with conventional clinical tests of muscle strength, 3DGA was used to measure ankle power generation because it is the single greatest power generation in the gait cycle and accurate no cost judgements can be made by clinicians. Although it may be argued that the relationship between ankle power generation and mobility may be due to high task
specificity, it was only measured at the initial assessment at a self-selected walking speed, and is less specific to the higher demands of hopping and skipping in the HiMAT. Nonetheless, this study has identified that clinicians may use judgements of push-off as the main predictor of mobility outcome for ambulant patients and prioritizes it for treatment. The HiMAT was chosen as a measure of mobility because it is less susceptible to a ceiling effect than other scales used in neurological rehabilitation. Although it is a unidimensional scale, indicating that does not quantify the multi-dimensional requirements of cognitive ability for functional mobility, it does incorporate the higher level mobility skills required for return to employment, social, leisure and sporting activities.

Conclusions

The ability to generate ankle joint power during push-off was a strong predictor of mobility outcome after a period of six months of rehabilitation. Motor skill performance was also a predictor of mobility outcome. Balance disorders were prevalent and improved with rehabilitation, yet contributed to only a limited extent to the level of recovery in mobility.

References


Table 1. Participant Demographics at initial testing session (n=31).

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>26.2</td>
<td>9.6</td>
<td>17-54</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>175</td>
<td>10</td>
<td>147-187</td>
</tr>
<tr>
<td>Weight (kgs)</td>
<td>68.8</td>
<td>14.5</td>
<td>43-98</td>
</tr>
<tr>
<td>Time post-injury (months)</td>
<td>8.7</td>
<td>8.3</td>
<td>1.4-24.1</td>
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<tr>
<td>Post-traumatic amnesia (days)</td>
<td>60.8</td>
<td>32.8</td>
<td>14-123</td>
</tr>
</tbody>
</table>
**Table 2.** Summary and change scores for physical impairments and mobility performance (mean and SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Initial</th>
<th>6 month follow-up</th>
<th>Mean Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobility</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HiMAT</td>
<td>16.6 (10.2)</td>
<td>31.1 (13.5)</td>
<td>14.5 (9.7)*</td>
</tr>
<tr>
<td>Self-selected gait speed (m/s)</td>
<td>.88 (.39)</td>
<td>1.17 (.31)</td>
<td>0.29 (0.29)*</td>
</tr>
<tr>
<td><strong>Physical Impairments</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Balance score (sec)</td>
<td>27.3 (23.3)</td>
<td>43.5 (28.6)</td>
<td>16.2 (20.9)*</td>
</tr>
<tr>
<td>Strength (Watts/kg)</td>
<td>1.28 (.83)</td>
<td>1.92 (0.95)</td>
<td>0.64 (0.56)*</td>
</tr>
<tr>
<td>Spasticity (Tardieu)</td>
<td>3.9 (4.2)</td>
<td>3.3 (3.3)</td>
<td>0.6 (3.6)</td>
</tr>
<tr>
<td>Motor Skill Level (GPS)</td>
<td>10.6 (2.2)</td>
<td>10.8 (1.9)</td>
<td>-0.2 (1.4)</td>
</tr>
</tbody>
</table>

*Significant difference at retest $p < .001$