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A pilot study comparing the cognitive demand of walking for trans-femoral amputees using the Intelligent Prosthesis with that using conventionally damped knees

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Objective: To compare the cognitive demand of walking when using a conventional prosthesis with that using a microprocessor-controlled prosthesis.
Design: Ten unilateral transfemoral amputees wearing conventional pneumatic swing phase control (conventional prosthesis) prostheses walked on a treadmill which enforced a pattern of constantly varying speeds. The subjects simultaneously performed a simple or a complex distracting task. Following a period of accustomization, the subjects performed the same test wearing a prosthesis with microprocessor control of swing-phase damping (the Intelligent Prosthesis).
Outcome measures: The three-dimensional trajectory (sway) of a retroreflective marker attached to the forehead was measured by a video-based motion analysis system, and used as a measure of gait quality. The ratio of the sway for the complex task over the simple task (the 'automation index') was used as a measure of the degree of automation of gait.
Results: No significant differences were found in the automation index between the two devices. However, the total sway for the conventional prosthesis was significantly higher. Sway during the complex distracting task was significantly higher than during the simple task.
Conclusions: The microprocessor-controlled prosthesis was not found to be less cognitively demanding than a conventional prosthesis.

Introduction

In order to allow transfemoral amputees to walk with a free-knee prosthetic limb, damping of the prosthetic knee mechanism is required. This is usually achieved by a valve which controls the flow of fluid (hydraulic or air) through an orifice valve. Conventionally, the valve is adjusted by a prosthetist to provide the correct damping for the amputee's preferred walking speed. For walking speeds other than this the prosthesis may provide incorrect damping, which may force the amputee to compensate by introducing gait deviations, such as elevating the pelvis, or kicking the pros-

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thetic leg forward.[1] The Intelligent Prosthesis (Charles A Blatchford, Basingstoke, UK) seeks to alleviate this problem by using a microprocessor to actively control an orifice (by means of a needle valve and stepper-motor arrangement). Orifice diameter is adjusted as cadence varies, according to settings programmed by the prosthetist, thus damping is maintained at near optimal levels across a range of walking speeds.

The Intelligent Prosthesis has been evaluated for its effect on various gait parameters such as energetics,[1,2,3] symmetry[1] and subjective impressions.[1,4] One of the as yet untested claims made for it is that by reducing the need for the subject to compensate for inappropriate damping, the cognitive demand on the subject will be lessened. Zahedi[5] states 'Using this product . . . for the first time the amputee does not need to think about walking'. As part of a wide ranging assessment of the Intelligent Prosthesis (see also ref.[4] the present authors attempted to test this claim.

Walking is usually regarded as an activity requiring little or no cognitive effort.[6] However, walking with an above-knee prosthesis may present an increased cognitive load as the normal system of proprioceptive clues as to the prosthetic limb's position in space are lost, and must be substituted by increased reliability on other information such as vision.[7] Additionally, loss of motor control at the ankle and knee precludes some of the normal balance defence strategies, leading to the use of other less suitable strategies such as reliance on stump muscles and hip and trunk compensatory mechanisms.

A typical gait laboratory presents a rather artificial environment consisting of a flat, level, quiet, non distracting walk-path. In contrast, for real-world gait, a host of other cognitively demanding tasks may be concurrently performed, such as obstacle avoidance, route planning, uneven terrain negotiation, holding a conversation, etc. Interference between the primary task (gait) and secondary task may result in a reduced ability to perform the secondary task or even an impaired ability to walk, which could have safety implications. Thus the cognitive demand of walking may be an important factor which is hidden in most laboratory-based tests.

Geurts and Mulder[8] proposed a model to assess the cognitive demand of walking. They argued that a task that is not well automated requires a large amount of attention. If there are sufficient information-processing resources available then this may not affect performance. However, if a second, cognitively demanding task is performed simultaneously with the primary task there will be resource competition, leading to a reduction in cognitive resources available to the primary task, and hence reduced performance. For a secondary task with a fixed cognitive demand, the degree of task interference will reflect the 'automation' of the primary task. A well-automated skill will not suffer from the simultaneous performance of the concurrent task, whereas a nonautomated (highly cognitively demanding) skill will degenerate when exposed to interference from the secondary task. They applied this model to the standing balance control of a group of lower limb amputees during their rehabilitation period[6]: whereas measures of sway in a single task condition showed no change from the start to the end of the rehabilitation period, if a second task was added there was a significant improvement in balance control over the rehabilitation period. This demonstrated an improvement in the automation of the task during the rehabilitation period.

Our intention in this study was to apply a similar technique to investigate if there was a difference in the cognitive demand of walking between the two types of knee mechanism.

Methods

Ten subjects (7 male, 3 female, mean age 38 years, 8 amputations due to trauma, 2 due to malignancy) were recruited on to the study from existing patients at the Mobility and Specialised Rehabilitation Centre in Sheffield. The subjects chosen were all at least five years post amputation, had no stump problems, were generally fit and had a reasonably high level of activity, and so were assumed to be those that might benefit most from the new device. They were unilateral trans-femoral amputees wearing Endolite prostheses (Charles A Blatchford, UK) with suction polypropylene sockets, pneumatic swing phase control Endolite Stabilized Knees (ESK) and Multiflex ankles and feet.

On entering the study all subjects were fitted with a new conventional knee unit, a new cosmetic foam and a new ankle unit whilst retaining their original sockets. The same prosthetist (JH) fitted all limbs for all subjects. The cognitive demand tests were carried out a minimum period of six weeks after this, to allow accustomization to the new components. Following this first series of tests the patients were given a new Intelligent Prosthesis knee unit to replace the conventional unit, and another new ankle and cosmetic foam, the original sockets were again retained. Another minimum six-week accustomization period preceded the second set of cognitive demand tests.

All the subjects were long-term conventional prosthesis users who transferred to the Intelligent Prosthesis. This presents a fixed order in the testing of the devices which may weaken the study. The six-week accustomization period was chosen to allow sufficient time for use of the new device to become automated (English *et al.*[9] suggest a minimum of three weeks is allowed before gait stabilizes after a change of prosthetic component). Tests conducted at an earlier point in time (before automation occurred) would have been biased against the Intelligent Prosthesis.[6]

The tests consisted of a 60-second walk on a treadmill (Powerjog E series, Sports Engineering Ltd, Birmingham, UK). The treadmill was programmed to follow a constantly changing speed profile (accelerate from 0 to 4 km/h in the first 20 seconds, decelerate to 2 km/h in the next 10 seconds, accelerate to 4 km/h in the next 10 seconds, decelerate to stop in the final 20 seconds) in the expectation that any differences in the performance of the two knees would be greatest at constantly changing speeds as the conventional prosthesis is optimized for gait at one particular speed, whereas the Intelligent Prosthesis adapts to the current walking speed. This constantly changing speed also ensured that no subject walked for any significant period of time at his or her preferred walking speed. All subjects were given a period of training in treadmill walking on a previous visit to the unit. The subjects were asked to walk without using their hands for support.

The performance measure chosen was whole body sway, this was assessed by measuring the three-dimensional movements of a marker placed on the subject's forehead at 20-ms intervals using a video-based motion analysis system (Elite, BTS Milan). The forehead site was chosen to give a better integration of all gait deviations, including those of the trunk, than would a marker placed at the lumbar spine (a common site chosen for measurement of sway).

A computer monitor was placed on a stand in front of the subject, at a height that allowed easy reading. The secondary tasks were displayed on the monitor. Tasks one, three and five were a noncognitively demanding task, the counting task. This task was to read a number that cycled repeatedly from 1 to 10, changing once every second. Tasks two, four and six were a distracting task, the Stroop test, a well-validated, cognitively demanding task that has a negligible learning effect.[10] It was implemented by displaying random names of colours at random locations on the monitor screen, whilst printing them in further random colours. The subject was required to enunciate the colour in which the word is printed, whilst suppressing the tendency to read the word. New colour names were displayed every second. The number of mistakes the subjects made was recorded. Treadmill walking (as opposed to walking outside the laboratory) does not require a subject to visually monitor his or her immediate environment and may allow the subject's gaze (and thus head position) to wander. The use of a visual distracting test ensured that the subject's gaze remained focussed on the computer monitor; this is why the counting task was compared with the Stroop test (rather than having no secondary task). Nonvisual distracting tests (such as mental arithmetic) may also interfere with walking, but do not direct the subject's gaze.

The magnitudes of the three-dimensional marker displacements in each 20-ms period were summed to give a total distance travelled by the marker. This was divided by the duration of the trial to give a mean velocity. There was no order effect between the first and the last counting test and so the results of all three counting tests were combined; the same was true of the Stroop tests. The mean velocities for all three Stroop tasks performed wearing the conventional prosthesis were divided by the mean velocities for all three counting tasks to give a ratio. A value of this ratio greater than one would indicate that performance (as measured by deviation of the head marker) is degraded whilst performing the Stroop task relative to the simple counting task.

The Stroop and counting velocities for all subjects were averaged to produce a mean sway velocity for each limb type. This measure is designed to show any overall differences between the limbs that are not just due to cognitive factors.

The conventional prosthesis and Intelligent Prosthesis velocities for all subjects were averaged to produce a mean velocity for each test type. This will show if there are any differences between the interference produced by the two secondary tests.

All calculations were performed using Matlab (the Mathworks Inc.).

The study had the approval of the Northern General Hospital Ethics Committee.

Results

No subject gave more than two incorrect answers on any one Stroop test. This demonstrates that the requisite amount of attention was being given to this distracting task.

The results for each subject are shown in Table 1.

For five subjects the ratios fell by more than 1% for the Intelligent Prosthesis compared to the conventional prosthesis, for two subjects the ratios rose by more than 1% for the Intelligent Prosthesis. On average, for all subjects, the ratios were 1.8% smaller for the Intelligent Prosthesis than for the conventional prosthesis, but this is not significant at the 5% level ($p = 0.25$, two-tailed paired *t*-test).

For the conventional prosthesis the mean velocity for both tests was 212 mm/s, for the Intelligent Prosthesis it was 185 mm/s, this difference is significant ($p = 0.047$, two-tailed paired *t*-test).

For the counting test the mean velocity for both limbs was 193 mm/s, for the Stroop test it was 204 mm/s. This difference is significant ($p = 0.0005$, two-tailed paired *t*-test).

Discussion

No significant difference was seen between the ratios of sway for the complex versus the simple distracting tasks for each prosthesis, thus it was not demonstrated that the Intelligent Prosthesis has a smaller cognitive burden during gait at different speeds. There may be genuine small differences which this study with only 10 subjects did not have the power to detect. Alternatively there may well be no genuine differences: the subjects all used their conventional prosthesis for several years before switching to the Intelligent Prosthesis and one might expect its use to be well automated by this time. It might be interesting to compare the cognitive demand of the two devices during the period when new amputees first learn

Table 1 Sway velocities and ratios for each subject

Subject	Mean velocity (mm/s)		Conventional prosthesis ratio Stroop/counting	Mean velocity (mm/s)		Intelligent Prosthesis ratio Stroop/counting	Difference in ratios (Intelligent Prosthesis-conventional prosthesis) (%)
	Conventional prosthesis counting	Conventional prosthesis Stroop		Intelligent Prosthesis counting	Intelligent Prosthesis Stroop		
1	261	285	**1.09**	145	168	**1.16**	+7%
2	278	297	**1.07**	277	280	**1.01**	−6%
3	228	235	**1.03**	168	177	**1.05**	+2%
4	205	213	**1.04**	182	185	**1.02**	−2%
5	164	188	**1.15**	152	171	**1.12**	−2%
6	188	193	**1.03**	187	192	**1.02**	0%
7	225	236	**1.05**	246	257	**1.04**	0%
8	142	152	**1.07**	128	131	**1.02**	−5%
9	179	199	**1.11**	157	160	**1.01**	−10%
10	188	195	**1.04**	168	173	**1.03**	−1%

Clinical messages

- Gait using the Intelligent Prosthesis was not shown to be less cognitively demanding than using a prosthesis with a conventional knee mechanism.
- Total sway during gait was significantly less for the Intelligent Prosthesis than for the conventional prosthesis. This result requires further investigation to characterize the differences.
- Total sway during gait was significantly greater for a cognitively demanding distracting task than for a simple distracting task for both prostheses, showing that there is interference between quality of walking and concurrent distracting tasks. This might suggest that gait measured in the laboratory (a single task mode) is artificially good.

to use a prosthetic limb. However, due to the increased variability of a non—paired study, the sample size would need to be large to pick up any differences.

The mean sway velocity whilst performing the Stroop test was shown to be significantly larger than for the simple counting test. This indicates that there is an interaction between the primary task (gait) and the secondary task, the degree of the interaction is greater for the cognitively demanding task. It also demonstrates that displacement of a forehead-mounted marker is a sufficiently sensitive measure to detect these differences.

The significant difference in the mean sway velocity between the two prostheses is surprising. This might be due to an order effect, as the conventional prostheses were all tested first and there might have been an improvement in treadmill walking ability by the time of the second test. However, given the relatively long period of time without any treadmill walking between tests this seems unlikely. It may well represent reduced gait deviations when wearing the Intelligent Prosthesis compared to the conventional prosthesis; however, a full body kinematic analysis will be needed to confirm this.

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