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Use of an instrumented treadmill for real-time gait symmetry evaluation and feedback in normal and trans-tibial amputee subjects

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Abstract

The purpose of this research was to evaluate a newly developed system for assessing and providing feedback of gait symmetry information in real time to subjects walking on a motorised treadmill (the CCF Treadmill). The advantages of the system are that it allows the rapid collection and comparison of temporal and kinetic parameters of gait for multiple successive strides, at a constant known speed, without forcing subjects to target their footsteps. Gait asymmetries of six normal (mean age 42.7 years) and six unilateral trans-tibial amputee subjects (mean age 41.7, and average 6.0 years using a prosthesis) were quantified. The amputee group was the re-evaluated after receiving five minutes of training with each of three different types of real-time visual feedback (RTVF). Asymmetries in the measured parameters before feedback were 4.6 times greater in the amputee population than in the normal group, and were consistent with the finding of previous authors. Significant decreases in gait asymmetry were demonstrated for all forms of feedback after amputees received feedback training. Results, however, indicate that gait asymmetries for different variables are not necessarily related, and that more work needs to be done to identify those variables for which attaining a more symmetrical gait pattern is most beneficial. Further work also needs to be done to determine the long term effects of such RTVF training. The CCF Treadmill and RTVF were shown to be potentially useful tools both for defining rehabilitation targets and for quantifying patients' progress towards those goals.

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Background and significance

Nearly sixty thousand major lower limb amputations are performed in the United States each year (DHHS Publication No. PHS 92-1774, 1992) and more than half of those are trans-tibial (TT) amputations (Wilson, 1989). The majority of amputees are elderly patients with peripheral vascular disease (PVD), usually related to diabetes mellitus (DeLuccia *et al.*, 1992; Harris *et al.*, 1991), and have poor general prognosis. As many as 45% of these patients are unable to master the use of a prosthesis (Moore *et al.*, 1989) and often become candidates for long term institutional care. The cost of caring for elderly amputee patients in the United States is expected to grow to as much as three billion dollars a year by the year 2000 (Cherner, 1993). Developing ways of improving rehabilitation outcomes could go a long way towards reducing these costs and providing a better quality of life for these patients.

In human gait, symmetry between left and right limbs can be measured for anthropometric, temporal, kinetic, kinematic, or electromyographic (EMG) data. Several authors have reported small, but consistent asymmetries in the timing (Rosenrot *et al.*, 1980; Hirokawa, 1989; Herzog et al., 1989), ground reaction force profiles (Herzog *et al.*, 1989), and kinematics (Gunderson *et al.*, 1989) of normal subjects. Herzog *et al.*, (1989) defined asymmetry as the ratio of the difference between the left and right values to the average of the two values times 100%, where perfect symmetry was given by SI = 0%. Asymmetries for 12 variables, extracted from the vertical force curves of 62 men and women were all within ±4%, with standard deviations ranging from ±2.0% to ±41.3% (Herzog *et al.*, 1989). Variables derived form the anteroposterior and mediolateral force curves exhibited greater asymmetries. These data suggest that there are slight asymmetries inherent even in normal gait. However, the magnitudes of asymmetry reported differed for different variables, suggesting that asymmetry is not a universal quality of gait, but is dependent upon the particular variable being measured.

Symmetry is an issue in the gait of amputees because of the unnatural asymmetry imposed on the biomechanical system by the prosthesis (Winter and Sienko, 1988). The most prominent asymmetries found in amputee gait have involved shortened stance times (Breakey, 1976; Cheung *et al.*, 1983; Skinner and Effeney, 1985; Seliktar and Mizrahi, 1986; Baker and Hewison, 1990) and decreased ground reaction forces (Skinner and Effeney, 1985; Seliktar and Mizrahi, 1986; Baker and Hewison, 1990) for the prosthetic limb compared to the natural limb. Most studies in the literature have focused on the qualitative description of gait asymmetries (Skinnner and Effeney, 1985), or quantitative measures based on raw differences (Breakey, 1976; Skinner and Effeney, 1985; Cheung *et al.*, 1983; Baker and Hewison, 1990), or ratios (Seliktar and Mizrahi, 1986) of values recorded for each limb. Lack of plantar flexion, and normal ankle motion has been described as the primary cause of most amputee gait deviations, including asymmetrical gait timing, knee joint motions, and increased muscle activities in both amputated and contralateral limbs (Breakey, 1976; Winter and Sienko, 1988). Loss of normal neuromuscular control and proprioceptive feedback functions have been cited as the major causes of the increased variability in gait timing between normal and amputee subjects (Zahedi *et al.*, 1987).

Cheung *et al.* (1983), reported that raw differences in total support times for four TT amputee patients decreased from 5.7% to 3.5% of the total stride time after six weeks of gait training. Similar results were reported by Baker and Hewison (1990) for asymmetries in single support times of twenty unilateral amputee subjects, indicating that these inherent gait asymmetries can be reduced with training. Bach *et al.* (1994) tested a computer simulation which adjusted inertial loading and mass distributions in the prostheses of five trans-femoral amputee patients in order to maximise swing phase symmetry. Significantly greater swing phase symmetry, reduced oxygen consumption, and increased subjective ratings were found for subjects wearing the symmetry optimised prostheses. These results support the idea that improved gait symmetry, at least for certain variables, is related to reduced energy expenditure, and is therefore an appropriate goal in rehabilitation.

Biofeedback techniques have been used in a variety of areas involving gait rehabilitation. Systems have been built which provide quantitative feedback of temporal (Hirokawa and Matsumura, 1989), kinematic (Fernie *et al.*, 1978), kinetic (Gapsis *et al.*, 1982), or EMG information (Colborne and Olney, 1990), or a combination of these. Such feedback is usually auditory (Fernie *et al.*, 1978) or visual in nature, or both (Hirokawa and Matsumura, 1989; Colborne and Olney, 1990). Gapsis *et al.* (1982) reported the use of a device (the Limb Load Monitor, or LLM) designed to provide auditory feedback of weight bearing information. The authors studied the rehabilitation outcomes of ten subjects with different gait disabilities using the LLM device compared with ten subjects matched for age and diagnosis who did not. The group of patients who used the LLM reached their goals in a significantly shorter period of time than did the control group (7.3±3.0 days versus 13.6±5.8 days, $p<0.001$) (Gapsis *et al.*, 1982). The same device was later used by Gauthier-Gagnon *et al.* (1986) to assist a group of TT amputees in early balance training. These studies demonstrate that biofeedback can be used to improve rehabilitation outcome.

The purpose of the research reported here was to evaluate a newly developed system for assessing and providing feedback of gait symmetry information in real time to subjects walking on a motorised treadmill. The system involved the use of a specially designed device (the "CCF Treadmill") with two force plates mounted under the treadmill belt (Dingwell and Davis, 1995). The CCF Treadmill was used to compare various parameters of gait symmetry between two groups of normal and TT amputee subjects, and to evaluate the effectiveness of Real-Time Visual Feedback (RTVF) training at reducing gait asymmetries for the TT amputee subjects. Amputee patients are currently evaluated in a subjective manner by trained prosthetists (Kapp and Cummings, 1992), and quantitative gait analyses are usually not performed. There are often difficulties associated with standard gait analysis techniques that require subjects to perform multiple trials walking over ground and placing ther feet on one or more force plates. The data collection effort can be quite costly and time consuming and thus unsuitable for providing "instantaneous" feedback to patients learning to walk in a rehabilitation setting. This study describes the use of a device that was built to address these issues and to improve and expand upon current gait analysis and rehabilitation techniques. It was anticipated that such a device could be an especially effective aid in a rehabilitative context where patients could receive RTVF during the gait retraining process.

Methods

The current research was performed using a specially designed treadmill/force plate device (the "CCF Treadmill") built at the Cleveland Clinic Foundation. The CCF Treadmill was based on previous treadmill/force plate designs (Kram and Powell, 1989; Davis *et al.*, 1991) and is described in more detail elsewhere (Dingwell and Davis, 1995). The primary advantage of this system is that it allows the collection and comparison of temporal and kinetic parameters of gait for both limbs for multiple, successive strides in real time. These comparisons can be made at a constant known speed, without forcing subjects to target their footsteps. With the use of this treadmill system, large amounts of data can be collected and analysed in a very short period of time. Ten to fifteen complete, consecutive strides of data can be collected in as little as 20 to 25 seconds. Under standard gait laboratory conditions, the collection of such data (for non-consecutive strides) would typically take over an hour to complete. This is an especially significant advantage when dealing with amputee subjects or other rehabilitation patients who cannot physically tolerate walking for more than a few minutes at a time.

Two AMTI force plates (Advanced Mechanical Technologies, Inc., Newton, Massachusetts), model OR6-1, were bolted to an aluminium mounting platform inside the treadmill such that the top surface of the force plates was directly underneath the treadmill belt. The mounting of the force plates has been described by Dingwell and Davis (1995). The treadmill was mounted such that the surface of the treadmill belt was even with the laboratory floor and was further modified to include two adjustable hand rails, mounted on either side of the treadmill and a monitor stand bolted in front of the treadmill to provide subjects with RTVF displays. The setup for the CCF Treadmill is shown in Figure 1. Data were collected and analysed on a Gateway 2000 IBM compatible 486 DX2 computer (© Gateway 2000, Inc.).

Software was written to continuously collect, process, and display gait symmetry information in real time at collection frequencies of up to 100 Hz. Three different displays of RTVF were developed. Each feedback routine was chosen to represent a different type of gait information. The Centre Of Pressure (COP) display was designed to draw the centres of pressure calculated for the left and right feet as the subject walked on the treadmill. Figure 2 (top) shows a representation of this output display, with the superimposed centre of pressure paths for three full strides of gait for both limbs. The divided rectangle shown on the screen represented the top view of the two forces plates in the treadmill. This display traced the path of the subjects' feet as they walked on the treadmill, allowing them to see any differences in the length of stride for either foot, or if the either foot was leading or lagging behind the

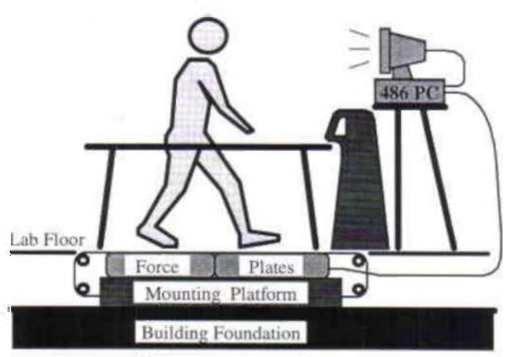

Fig. 1. CCF Treadmill set-up for real-time gait analysis and visual feedback.

other (e.g. the right foot in Figure 2 appears to be slightly leading the left foot at heel strike).

The Percent Stance Time (%ST) display was based on the algorithm's ability to determine times of occurrence of heel strike and toe off. Times of heel strike and toe off were extracted from the time derivative of the smoothed mediolateral position of the centre of pressure curve (d/dt(Dx)). The d/dt (Dx) curve was approximately zero during mid stance, and showed distinct positive and negative peaks when weight was shifted from each foot to the other (Dingwell and Davis, 1995). Stance times

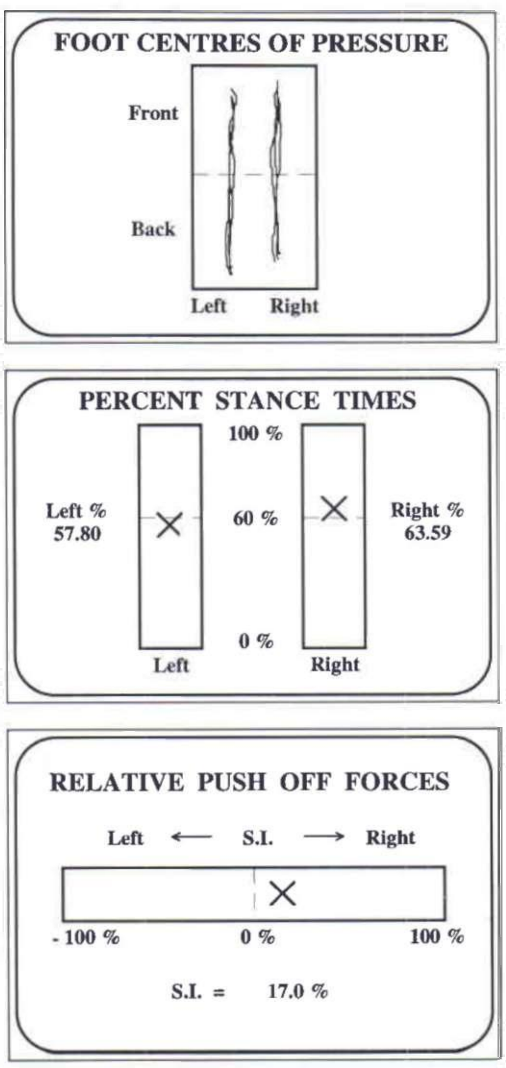

Fig. 2. Three different output displays for real-time visual feeback: COP display (top), %ST display (middle), and POF display (bottom).

were computed from heel strike and toe off times as a percentage of the total stride time by the following equation:

$$\%\ \text{Stance Time} = \frac{(\text{Toe Off} - \text{Previous Heel Strike})}{(\text{Heel Strike} - \text{Previous Heel Strike})} \quad (1)$$

and were displayed graphically for both left and right feet, as shown in Figure 2 (middle). A typical ratio of 60% is indicated by a horizontal dashed line, and the patient's actual data are given numerically and represented as X's on the vertical bar graphs.

Push Off Force (POF) was calculated based on the maximum force recorded on the rear force plate for each foot. An Index of Symmetry (SI) was calculated based on an equation modified from Herzog *et al.* (1989):

$$\text{SI} = \frac{(X_{\text{Right}} - X_{\text{Left}})}{(X_{\text{Right}} + X_{\text{Left}})} \times 100\% \qquad (2)$$

This equation produces an SI with a continuous linear range of values from -100% to +100% with perfect symmetry being equivalent to SI = 0%. The calculated SI value was displayed graphically on a horizontal bar graph (indicated by an 'X'), with the associated numerical value of SI also displayed. A representation of this display is shown in Figure 2 (bottom).

Six normal healthy subjects, with no previous history of lower limb injury, were selected to participate in the study. Subjects were selected whose ages were approximately in the age range of the amputee subjects, though no specific attempts were made to match normal and amputee subjects by age or sex. Mean age of normal subjects was 42.7 years (range 33 to 54 years). All subjects responded that they were right leg dominant when questioned. Six trans-tibial amputee subjects were selected from the patient data base from the Department of Orthotics and Prosthetics and the Cleveland Clinic. All unilateral TT amputee patients who were in good general health, and were judged to be "established walkers," capable of tolerating twenty minutes of treadmill walking, were eligible to participate in the study. The six subjects chosen had a mean age of 41.7 years (range 31 to 69 years), and had been wearing their prostheses on average of 6.0 years (range 6 months to 21 years). Cause of amputation was traumatic in three cases, related to cancer or other illness in two cases, and peripheral vascular disease in one case. All subjects participated on a volunteer basis, and signed appropriate informed consent forms.

Normal and amputee subjects were given four minutes of walking time to acclimatise to the treadmill, and initial asymmetry data was collected. All normal subjects walked at a pace of 2.5 km/hr (0.69 m/s) and amputee subjects walked at self-selected speeds with an average of 2.0 km/hr (0.56 m/s) (range 1.5 to 2.5 km/hr). No instructions were given to either normal or amputee subjects other than to walk normally and no subjects received any visual feedback at any time during treadmill acclimatisation or initial data collection. The TT amputee subjects were then given four minutes of RTVF training with each of the three feedback routines and data were again collected for that routine while the subject was receiving feedback. Subjects were allowed to rest briefly between feedback sessions as needed. While receiving feedback of symmetry information, subjects were instructed to adjust their gait patterns to achieve the most symmetrical gait possible for the particular feedback being given. Subjects received RTVF training in a pseudo-random fashion such that no two subjects were shown the three modes of feedback in the same order.

Three asymmetry variables were quantified for differences between left and right limbs from the RTVF data: foot placement at heel strike (anterior position of the centre of pressure, SI_{COP}), percent stance times ($SI_{\%ST}$), and maximum push off forces (SI_{POF}). The SI_{COP} variable was calculated to determine if amputee subjects tended to place either foot ahead of the other at heel strike (i.e. if they tended to "lunge" with either their sound limb or their prosthesis). SI_{COP}, $SI_{\%ST}$, SI_{POF} were evaluated before and after each respective feedback was given. In addition, a fourth asymmetry variable representing single support times (SI_{SST}) was quantified for all four conditions (before feedback, and after each of the three feedback sessions). This variable was examined to determine the effects of the different feedback modes on a variable not directly associated with the feedback parameter itself. SI_{SST} differs from $SI_{\%ST}$ in that the calculations for $SI_{\%ST}$ include the duration of double support, while $SI_{\%ST}$ does not (see Appendix). It was anticipated that double support times would be longer for amputee subjects than for normals, and would also be longer for amputees shifting weight from their sound limb to their prosthesis than vice versa. SI values for each variable were quantified for normal and amputee subjects using the following equations, modified from Herzog *et al.* (1989).

$$SI_{Normal} = \frac{(X_d - X_{nd})}{(X_d + X_{nd})} \text{ x } 100\% \qquad (3)$$

$$SI_{Amputee} = \frac{(X_n - X_p)}{(X_n + X_p)} \text{ x } 100\% \qquad (4)$$

Where "X" was the measured variable, "d" and "nd" represented dominant and non-dominant limbs, respectively, and "n" and "p" represented natural and prosthetic limbs, respectively.

Twenty five seconds of data, representing 10 to 15 complete strides of walking, were collected for all subjects for each of the specified conditions: normal subjects without feedback, and TT amputee subjects before and after receiving each type of visual feedback training. A variety of statistical tests was performed to compare asymmetries and variability in gait asymmetries between both groups of subjects, and to evaluate the effects of RTVF training. To compare average SI results to the condition of perfect symmetry (SI = 0), data for each subject was averaged, and one sample, two-tailed T-tests for means were performed for all four variables for both groups of subjects (n = 6 subjects per group). Single factor analysis of variance (ANOVA) tests with repeated measures were performed to compare asymmetry data from normals to that for amputees. To determine if amputees showed greater variability in gait asymmetry, standard deviations for ten strides of gait for each subject were computed and compared using a one-tailed T-test for samples of equal variance. To determine if symmetry between different variables of gait were related, the symmetry values for ten strides of gait were averaged for each subject for each variable and correlations between the average values were computed for both groups. The effects of RTVF on the symmetry of TT amputee gait were analysed using a two factor ANOVA with repeated measures to determine differences before and after feedback training for the three RTVF

Table 1. Symmetry indices for normal and amputee subjects. (Mean (average std. dev.) for n = 6 subjects x 10 strides per subject)
(* = significantly different to SI = 10 at p<0.01)

Variable	Normals	Amputees	p - value
SI_{COP}	–0.18% (1.56%)	–1.54% (1.31%)	0.380
$SI_{\%ST}$	+1.84% (1.31%)	+6.98% (3.25%)*	**0.015**
SI_{POF}	–1.36% (2.08%)	+2.56% (2.97%)	**0.015**
SI_{SST}	+2.47% (2.39%)	+10.57% (4.96%)*	**0.014**

variables quantified (SI_{COP}, $SI_{\%ST}$, and SI_{POF}). Data for single support times were collected for all four treatments and a two factor ANOVA with repeated measures was performed to analyse differences between treatments. Individual differences were then compared using the method of least significant differences.

Results

All of the asymmetries quantified for normal subjects were less than 2.5%. Comparison of these data to the condition of perfect symmetry showed that none of these asymmetries were statistically different to a value of SI = 0 (p >0.10). Data for TT amputee subjects demonstrated significant non-zero asymmetries for $SI_{\%ST}$ and SI_{SST} (p<0.01) each). Asymmetries for SI_{COP} and SI_{POF} did not quite achieve the 0.05 level of significance (p = 0.07 each).

Table 1 shows mean SI values (n = 6 subjects) and ANOVA results comparing asymmetries of normal and amputee subjects. Means (n = 6 subjects) of standard deviations in SI (n = 10 strides per subject) are shown in parentheses. Amputees demonstrated significantly greater asymmetries than normal subjects for three of the four measured variables; $SI_{\%ST}$, SI_{POF}, and SI_{SST} and asymmetries for all variables were an average of 4.6 times greater for amputees than for normal subjects. T-tests comparing variabilities of both groups of subjects showed that TT amputee subjects demonstrated greater average variability in three of the four variables quantified; however, this difference was only significant for $SI_{\%ST}$ data (p = 0.03). Increases in variability of push off force and single support time for asymmetries (SI_{POF} and SI_{SST}) for TT amputees were not quite significant (p = 0.11 and 0.06 respectively).

Table 2. Correlations between average symmetry variables
(* = significant at p<0.05, ** = significant at p<0.01))

Normal Subjects (n = 6)			
Variable	SI_{COP}	$SI_{\%ST}$	SI_{POF}
$SI_{\%ST}$	**0.830***	–	
SI_{POF}	–0.361	–0.569	–
SI_{SST}	**0.862***	**0.996****	–0.598
TT Amputee Subjects (n = 6)			
Variable	SI_{COP}	$SI_{\%ST}$	SI_{POF}
$SI_{\%ST}$	0.338	–	
SI_{POF}	0.554	**0.926****	–
SI_{SST}	0.279	**0.986****	**0.869***

Results of correlations between the average values of the four variables quantified are shown in Table 2. Significant correlations were computed between asymmetry values for SI_{COP}, $SI_{\%ST}$, SI_{SST} for normal subjects, and between $SI_{\%ST}$, SI_{SST}, and SI_{POF} for TT amputees. The remaining six correlations were not significant.

Results of ANOVA analyses comparing changes in asymmetries for TT amputee subjects before and after RTVF training are shown in Table 3, and Figure 3. Significant decreases in the degree of assymetry were demonstrated for all three variables after amputees were shown visual feedback of the data.

Table 3. Average symmetry index values before and after feedback training
(Means for n = 6 subjects x 11 strides per subject)

Variable	Before	After	p - value
SI_{COP}	–1.58%	–0.56%	**0.002**
$SI_{\%ST}$	+7.03%	+5.18%	**0.007**
SI_{POF}	+2.47%	+1.38%	**0.033**

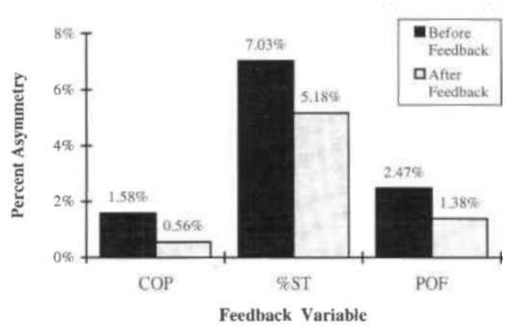

Fig. 3. Improvement in symmetry indices after real-time visual feedback training.

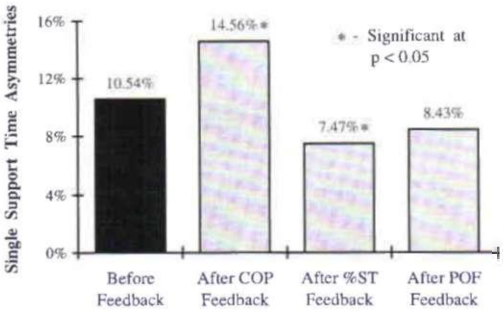

Fig. 4. Changes in single support time asymmetry (SISST) After real-time visual feedback training. (* – significantly different to before feedback at $p < 0.05$).

ANOVA results comparing asymmetries in single support times (SI_{SST}) between the four tested conditions indicated significant differences before and after RTVF training and the method of least significant differences was used to determine which feedback routines significantly affected SI_{SST} asymmetries. These results are shown in Figure 4. SI_{SST} data measured before feedback training showed a significant increase after COP feedback training ($p<0.05$), a significant decrease after %ST feedback training ($p>0.05$), and no significant change after POF feedback training.

Discussions

T-tests comparing average asymmetries of six normal and six TT amputee subjects to a perfect symmetry value of SI = 0 showed that only two of the eight comparisons were statistically significant. However, tests on larger groups of subjects might reveal these asymmetries to be significant. The results of the current study agree qualitatively with the findings of other authors regarding asymmetries in temporal gait patterns (Rosenrot *et al.*, 1980; Hirokawa, 1989) and ground reaction forces (Herzog *et al.*, 1989) of normal subjects. The asymmetries quantified in the current study were slightly greater than those reported by Herzog *et al.*, (1989). Possible reasons for this include the fact that Herzog's data were obtained on a larger sample of subjects than was used in this study. Additionally, subjects in this study were asked to walk at a pace of 2.5 km/hr (0.96 m/s) in order to obtain data more easily comparable to that collected for the TT amputee subjects. Gait patterns of normal subjects have been shown to be more consistent at preferred walking velocities (Rosenrot *et al.*, 1980). Therefore, and increase in the asymmetries of normal subjects' gait patterns may have resulted from asking them to walk at a pace slower than their normal velocity.

Asymmetry values from Table 1 demonstrate that TT amputees spent a significantly reduced time in total stance ($SI_{\%ST}$ = +6.98%) and single stance (SI_{SST} = +10.57%) on their prosthetic limb compared to their natural limb. Although TT amputees also generated less force at terminal stance on their prosthetic limbs (SI_{POF} = +2.57%), this difference was not significant. These increases in temporal asymmetries ($SI_{\%ST}$ and SI_{SST}) and peak force magnitudes (SI_{POF}) agree with the findings of previous researchers regarding the timing and force profiles of amputee gait patterns (Skinner and Effeney, 1985; Breakey, 1976; Cheung *et al.*, 1983; Seliktar and Mizrahi, 1986; Baker and Hewison, 1990). The variability in stride to stride asymmetries of amputees was greater than that of normals for three of the four variables quantified, although this difference was significant only for percent stance time asymmetry. This increase in variability could de due to the loss of normal neuromuscular control in the amputated limb (Zahedi *et al.*, 1987), to an imperfect socket fit resulting in motion occurring between the stump and the prosthesis, or a combination of these factors. Further investigation should be conducted to confirm these results.

Significant correlations were found between percent stance time and single support time asymmetries for both the normal and amputee subjects and also both percent stance time and single support time asymmetries, and push off force asymmetry for the TT amputee subjects. These positive correlations lend support to the theory that asymmetries in gait cycle timing are directly influenced by a loss of normal push off force in the gait of TT amputees (Breakey, 1976; Winter and Sienko, 1988). However, none of the six remaining correlations was significant, and three were in fact negative, suggesting that while asymmetries of certain variables might be related to each other, the asymmetries of other variables, in general, are not. This idea was supported by the ANOVA results examining the effects of visual feedback training on single support time asymmetry (SI_{SST}) which demonstrated that decreases in asymmetry for those variables being displayed were not necessarily reflected in improved symmetry for other parameters of gait. The TT amputee subjects may have in fact altered their gait patterns to decrease one form of asymmetry by increasing other asymmetries. No known study to date has adequately addressed the questions of how asymmetries measured for different variables are related, or what magnitudes of asymmetry for any of these parameters are necessary to adversely affect gait. In this respect, for future studies trying to use such RTVF to improve rehabilitation outcome, it would be advantageous to identify those specific variables for which attaining a more symmetrical gait would have the greatest consequence for long term benefit.

The results in Table 3 show that asymmetries in the gait patterns for all three feedback variables were significantly reduced after subjects trained with RTVF. These results demonstrate that subjects have the ability to manipulate their walking patterns based on the visual feedback information being given. The subjects of Cheung *et al.* (1983) showed a reduction in asymmetry of percent stance time from +3.7% to +2.4% after six weeks of gait training, a 35% change in asymmetry. Subjects from the current study showed percent times of +7.03% and +5.18% before and after visual feedback training, and effective reduction in asymmetry of 26% in only five minutes. These results, although encouraging, must be interpreted with caution for two primary reasons; it is not yet known whether subjects would be able to maintain these decreased asymmetries in the absence of visual feedback, and it is also not yet clear that these controlled changes in gait symmetry would result in long-term learning of a more symmetrical gait pattern. Since the primary goal of this project was to determine if amputee subjects could respond positively to RTVF, and since this was shown to be the case, the questions of long term gait training effects are left to future research.

Conclusions

The primary objectives of the current study were to evaluate the gait asymmetry characteristics of a group of normal subjects compared to a group of TT amputee subjects, and to evaluate the effectiveness of giving TT amputee patients RTVF training of gait symmetry information. The normal subjects studied did not demonstrate significantly asymmetrical gait patterns though small asymmetries were recorded. The asymmetries measured in TT amputee gait patterns were greater than those of normal subjects, and agreed qualitatively with asymmetries previously reported in the literature (Breakey, 1976; Cheung *et al.*, 1983; Seliktar and Mizrahi, 1986; Baker and Hewison, 1990). These increases in gait asymmetry are most likely due to the mechanical asymmetries imposed by the prosthesis (Winter and Sienko, 1988) and the loss of normal neuromuscular control and proprioceptive feedback in the amputated limb (Zahedi *et al.*, 1987). RTVF training was shown to be an effective means of producing significant short term reductions in the gait asymmetries of these amputee subjects.

Quantifying asymmetries in amputee gait patterns as they relate to normal subjects is the first step in trying to define what degree of asymmetry is acceptable, or desirable in patients' gait patterns during the rehabilitation process. Devices such as the CCF Treadmill can be useful tools both for defining and quantifying rehabilitation targets, and for measuring patients' progress towards those targets over a period of time. The results of this study should be taken as encouraging, but further study of gait asymmetries needs to be conducted in two areas; first, to identify and define the relationships between asymmetries measured for different variables and their functional relationship to the process of ambulation, and second, to determine the long term rehabilitation benefits of gait retraining with RTVF.

Appendix

Single support time asymmetries (SI_{SST}) were quantified to determine the effects of different feedback modes on a gait parameter not directly associated with the feedback. Although SI_{SST} and $SI_{\%ST}$ were shown to be strongly related, they were different variables in that SI_{SST} omitted the duration of double support. If the gait cycle for a given subject was 1 second long, with 0.62 and 0.58 seconds spent in total support on the sound and prosthetic limbs, respectively, and if the duration of double support were 0.1 seconds, the calculations of $SI_{\%ST}$ and SI_{SST} (from equation 4) would produce the following results:

$$SI_{\%ST} = \frac{(X_n - X_p)}{(X_n + X_p)} \text{ x } 100\%$$

$$= \frac{(62\% - 58\%)}{(62\% + 58\%)} \text{ x } 100\% = 3.33\% \quad (5)$$

$$SI_{SST} = \frac{(X_n - X_p)}{(X_n + X_p)} \text{ x } 100\%$$

$$= \frac{(0.52s - 0.48s)}{(0.52s + 0.48s)} \text{ x } 100\% = 4.00\% \quad (6)$$

If, however, the duration of double support were increased to 0.15 seconds, $SI_{\%ST}$ would remain unchanged, but the calculation of SI_{SST} would become:

$$SI_{SST} = \frac{(X_n - X_p)}{(X_n + X_p)} \text{ x } 100\%$$

$$= \frac{(0.47s - 0.43s)}{(0.47s + 0.43s)} \text{ x } 100\% = 4.44\% \quad (7)$$

Thus for the same percent stance times, SI_{SST} will be greater than $SI_{\%ST}$, and SI_{SST} will increse as the duration of double support increases. This can be seen in the data from Table 1 where SI_{SST} data were greater than $SI_{\%ST}$ data, and SI_{SST} data were also higher for TT amputees than for normal subjects. These data support the notion that amputees spend a greater portion of time in the double support phase of gait, probably to ensure better stability during locomotion.

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