Optimisation of the prescription for trans-tibial (TT) amputees

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Abstract

The great diversity of prosthetic mechanisms available nowadays leads to the question of which type of artificial foot would be the most advisable for a particular person. To answer correctly, it is necessary to establish, in an objective way, the performance of each type of prosthetic mechanism. This knowledge is obtained by means of the study of the subject-prosthesis interaction, both in static and dynamic conditions.

This paper, based on the analysis of 8 trans-tibial (TT) amputees, presents a quantitative method for the study of human gait which allows the determination of the influence of four different prosthetic ankle-foot mechanisms (SACH, Single-axis, Greissinger and Dynamic) on gait. To do this, 1341 gait trials at different cadences were analysed (383 with normal subjects and 958 with amputees, using the four prosthetic feet under study). From all the variables available for study only those which offered interpretable clinical information were chosen for analysis. A total of 18 variables (kinetic, kinematic and time-related) were selected. A covariance analysis (ANOVA) of these variables was made, which showed that the factors influencing TT amputee gait were, in order of importance, cadence and leg studied (sound or prosthetic), inter-individual variability and, finally, the prosthetic mechanism used. When looking at the performance during gait of the 4 prosthetic mechanisms studied it can be observed that there are similarities in the kinetic study between SACH and Dynamic feet on one hand and Single-axis and Greissinger feet on the other. These results seem to support the classification criteria of articulated and non-articulated prosthetic mechanisms.

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Introduction

Both the increasing demand for a better life standard on the part of the amputees, improving the functionality of gait and even taking part in sport activities, and the natural motivation of competitiveness on the part of the manufacturers are encouraging the orthopaedic industry to progress with the development of new prosthetic devices. Nowadays, the possibilities of selection (among prosthetic designs) are so many that an individual's needs can be partially satisfied by different means, which makes it difficult to select the ideal product. In general terms the basis for a correct orthopaedic prescription is suiting the features offered by a device to the user's functional needs. This demands, in the first place, a knowledge of the performance of the different prosthetic mechanisms, both in static conditions and during use; and, in the second place, it is also necessary to know the functional needs of the intended user.

Few scientific reports address the question of making comparative analyses of different prosthetic mechanisms, and those few merely compare some of their characteristics separately (Arya *et al.,* 1995; Casilla *et al,* 1995; Ehara *et al.,* 1993; Goh *et al.,* 1984; Schneider, 1993; Wing and Hittenberger, 1989). Additionally, the parameters analysed during gait and the methods used to obtain them vary from author to author. As a consequence, the comparison of the results of different research works and, consequently, the comparison of the different prosthetic mechanisms, becomes very difficult, if not impossible. Furthermore, the objective evaluation of the functional needs of the subject to be fitted is a question still to be solved and, maybe, a more complex matter than it seems.

If only the gait function is considered it is known that it is conditioned by numerous factors (Hoyos, 1984; Viosca, 1993):

- Individual factors: *age* (Gabell and Nayak 1984; Sudarsky, 1990), *sex* (Bhambhani and Sing, 1985; Jansen *et al,* 1982; Zuniga and Leavitt, 1973) and *interindividual variability* (Mann, 1981; Menard *et al,* 1992).
- Dynamics of gait: *velocity* (Murray *et al.,* 1984) or *cadence* (Ayora, 1990; Boonstra *et al,* 1993)
- Environmental: *ground surface* or *shoe type* Jones *et al,* 1986).
- Amputation: *etiology* (Pohjolainen *et al,* 1989; Sulzle *et al,* 1978), *surgical procedure* (Burgess and Moore, 1977; Murdoch, 1984; Steinbach *et al,* 1982), or *amputation level* (Sengler, 1984; Skinner and Effeney, 1985; Waters *et al,* 1976).
- Prosthesis: *fitting* (Meier *et al,* 1973;Mizrahi *et al,* 1985; Saxena and Mukhopadhyay, 1977), *alignment* (Pearson *et al,* 1973; Radcliffe, 1962) *or prosthetic mechanism.*

It can be seen then that the solution to the problem is complex and depends on many factors, It is thus necessary to come up with a common method for the analysis of prosthetic gait which, considering the above mentioned factors, allows for the comparison of the results drawn from different research teams, and therefore, for the comparison of different prosthetic mechanisms. This would mean an important saving of effort, while it would solve many of the problems posed.

The purpose of this work is to provide solutions to some of the drawbacks mentioned, To do this, the first aim is to present an objective and quantitative method for the study of prosthetic gait, which allows for the comparison of gait patterns. This will lead to the second objective, the comparison of the dynamic behaviour of 4 prosthetic ankle-foot mechanisms used by TT amputees, through the modifications introduced in the gait parameters. Although this does not mean solving the problem of assessing the amputees' functional needs, it will give objective data about the performance of the different mechanisms and therefore mean a first approach to the solution of the prosthetic prescription in clinical practice.

Methodology

The work has been developed following an accurate experimental procedure detailed below. In order not to confuse the variability due to the prostheses with that due to the individual nature and circumstances of the amputation or the amputee, the sample for the study was selected to be as homogeneous as possible so that the only source of variability was the prosthetic mechanism.

The gait analysis was carried out in a group of 8 TT amputees and 7 non-amputees. The amputees were fitted with patellar-tendon-bearing (PTB) prostheses and they fulfilled the following requirements: male; age between 18 and 50; traumatic TT amputation at least two years prior to the experience; good shaped stump free from skin problems, suture defects or hypertrophic scars; not suffering from any concurrent illnesses and having a high or very high level of functional gait activity according to Day's scale (Day, 1981), The control group were 7 non-amputated subjects, in good health condition, with normal gait and anthropometric characteristics similar to those in the amputee group.

The data of the two groups are shown in Tables 1 and 2.

Four prosthetic feet were studied, each representative of one of the families of articular devices most commonly used in the authors' hospitals (SACH, Single-axis, Greissinger and Dynamic). These feet were mounted on a copy of the amputee's prescribed prosthesis and were interchanged at random, allowing for a two-week adaption period before measurement.

All prostheses were made by the same manufacturer, to ensure similar criteria of manufacture, fitting and alignment thus avoiding variability derived from these factors. In all cases Oxford shoes with a 25mm heel were used. The experimental sessions were carried out at the Laboratory of Human Gait and Movement Analysis at the Institute of Biomechanics of Valencia (IBV). The equipment used was:

- 12m long walkway instrumented with two DINASCAN-IBV© extensometric force plates (Sanchez-Lacuesta *et al,* 1992).
- A system of polycentric electrogoniometry for the measurement of both limbs-hip, knee and ankle angles on the sagittal plane (Cortes *etal,* 1992).

Table 1. Characteristics of the amputee group, m = mean, s = standard deviation.

	Age	Mass (kg)	Height (cm)	Side amp	Day
VAM	37	66.5	170	L	15
API	19	64.0	176	L	24
MLT	26	55.0	174	R	36
EPF	47	76.0	171	R	14
JGM	35	65.0	175	L	39
JUM	43	71.0	168	R	22
BFO	49	90.0	164	L	14
MCF	21	43.0	153	L	26
m/s	34.6/11.5	66.3/13.9	168/7.5		23.7/9.6

- Telemetry equipment for the transmission of signals from the electrogoniometers.
- Data acquisition and control system which combines the signals from the platforms with those from the electrogoniometers and a PC with the appropriate software for data processing.

After a period of adaption to the laboratory conditions and the equipment used, and with the purpose of studying gait in a wide range of cadences, the subject was asked to walk at free cadence and, then, faster and slower until a spectrum of cadences ranging from 60 to 140 steps per minute was obtained. No metronome was used to measure cadence since it conditioned excessively the asymmetrical gait of the amputee. Instead, the period (T) which took them to walk five steps was timed in seconds and then calculated cadence (C) C = 5x (60/T), expressed in steps/min.

A total of 1341 trials of gait were made at different cadences, 958 of which corresponded to amputees and 383 to normal subjects. From all the variables which could be studied those selected for analysis were the ones that, in the authors' opinion, gave better clinical information on gait. A total of 18 variables was selected (Figs. 1 and 2); 7 were kinetic, 10 kinematic and 1 time-related (Single Support Stance Time SST). All of them are easy to interpret and were related to mechanical or physiological events in the gait cycle.

Table 2. Characteristics of the control group, m = mean, s = standard deviation.

	Age	Mass (kg)	Height (cm)
ACF	31	67.7	167
EMV	32	64.7	167
AHF	29	65.2	170
EVH	33	74.1	171
FSL	30	53.3	165
MVM	50	78.8	166
IPS	19	67.0	183
m/s	32/9.2	67.2/8	170/61

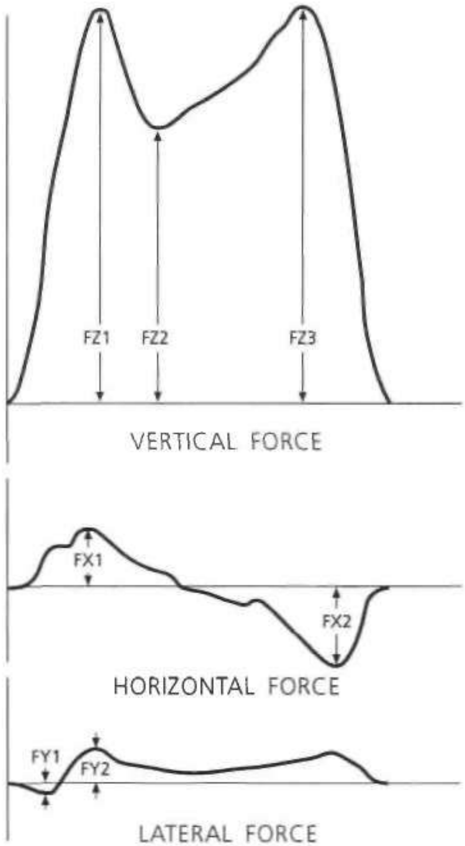

Fig. 1. Kinetic parameters.

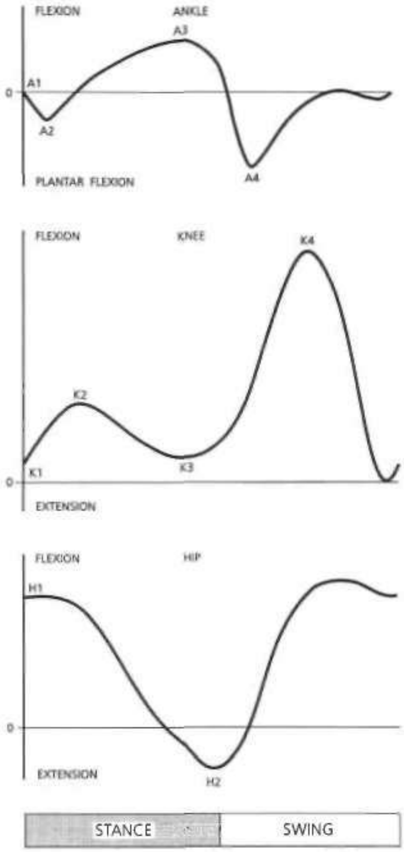

Fig. 2. Kinematic parameters.

The data were processed using BMDP Statistical Software and a co-variance analysis was done with the 18 variables selected. *Cadence* was set as covariable and *subject* (NAME), *limb considered* - sound or prosthetic - (SP) and type of *prosthetic mechanism* used (FOOTTYPE) were set as factors. The analysis of the Snedecor's F magnitude allows the controlled factors to be sorted according to their relative importance on the variable analysed.

Whenever significant differences were found a multiple linear regression analysis was performed with the purpose of adjusting evolution patterns of the dependent variables analysed as a function of cadence for each limb considered and prosthetic mechanism used. Only those graphs with a significant coefficient R of multiple correlation ($p < 0.01$) were considered.

Results and discussion

The results of the ANOVA showed that cadence, subject (NAME), limb studied (SP) and type of prosthetic mechanism used (FOOTTYPE) have a significant ($p < 0.05$) or highly significant ($p < 0.01$) influence on most of the variables analysed (Cortes, 1993). As can be seen in Table 3, the order of importance of the controlled factors with regard to the variables is, in the first place, cadence and limb studied (SP), in the second place, subject (NAME) and, in the last place, type of articular mechanism used (FOOTTYPE).

Consequently, the gait variables studied are greatly influenced by cadence. This suggests that gait trials should be performed in a wide range of cadences. Most of the experimental works reviewed (Doane and Holt, 1983; Enoka *et al,* 1982; Hoy *et al,* 1982; Winter and Sienko, 1988;) aim at the study of the influence of the type of prosthetic mechanism on gait although they neither consider cadence in a complete way nor the nature of the limb studied (sound or prosthetic). The results of this study show that these factors have greater influence on the dependent variables analysed than the type of articular mechanism used. This might explain the fact that the results published are not coincident.

Figure 3 depicts the relationship between kinetic variables and cadence for each type of articular mechanism. It can be observed, generally speaking, that there are similarities in behaviour of SACH and Dynamic feet, on the one hand, and of Single-axis and Greissinger on the other. This refers both to the sound limb and the prosthetic one. Therefore, from a kinetic point of view, the results suggest that the most determinant factor related to the behaviour of prosthetic feet is the presence or absence of a joint which allows for plantar flexion.

Nevertheless, it is important to point out other particular items that are not under this general rule. Single-axis and Greissinger feet show a different behaviour with respect to variable FX1 (maximum fore-aft horizontal force at heel contact). This suggests that the Greissinger foot behaves as a non-articulated foot, with values for FX1 below those of the control subjects. This pattern of kinetic behaviour is kinetically supported by Enoka *et al.,* (1982) who did not detect the expected plantar flexion corresponding to the design. On the contrary, horizontal force (FX1) in the artificial limb with the Single-axis mechanism is much higher than with the other

Table 3. Summary of the ANOVA. Arrangement of statistically significant controlled factors according to their relative importance.

Variable	1st	2nd	3rd	4th
FZ1	Cadence	SP	Name	Foottype
FZ2	Cadence	SP	Name	Foottype
FZ3	SP	Cadence	Name	Foottype
FX1	SP	Cadence	Name	Foottype
FX2	SP	Cadence	Name	Foottype
FY1	Cadence	SP	Name	Foottype
FY2	Cadence	SP	Name	
H1	Name	Cadence	Foottype	SP
H2	Cadence	Name		
K1	SP	Cadence	Name	Foottype
K2	SP	Cadence	Name	
K3	SP	Name	Foottype	
K4	Cadence	SP	Name	Foottype
A1	Name	SP	Foottype	
A2	Foottype	Name		
A3	SP	Name	Cadence	Foottype
A4	SP	Name	Cadence	Foottype
SST	Cadence	SP	Name	Foottype

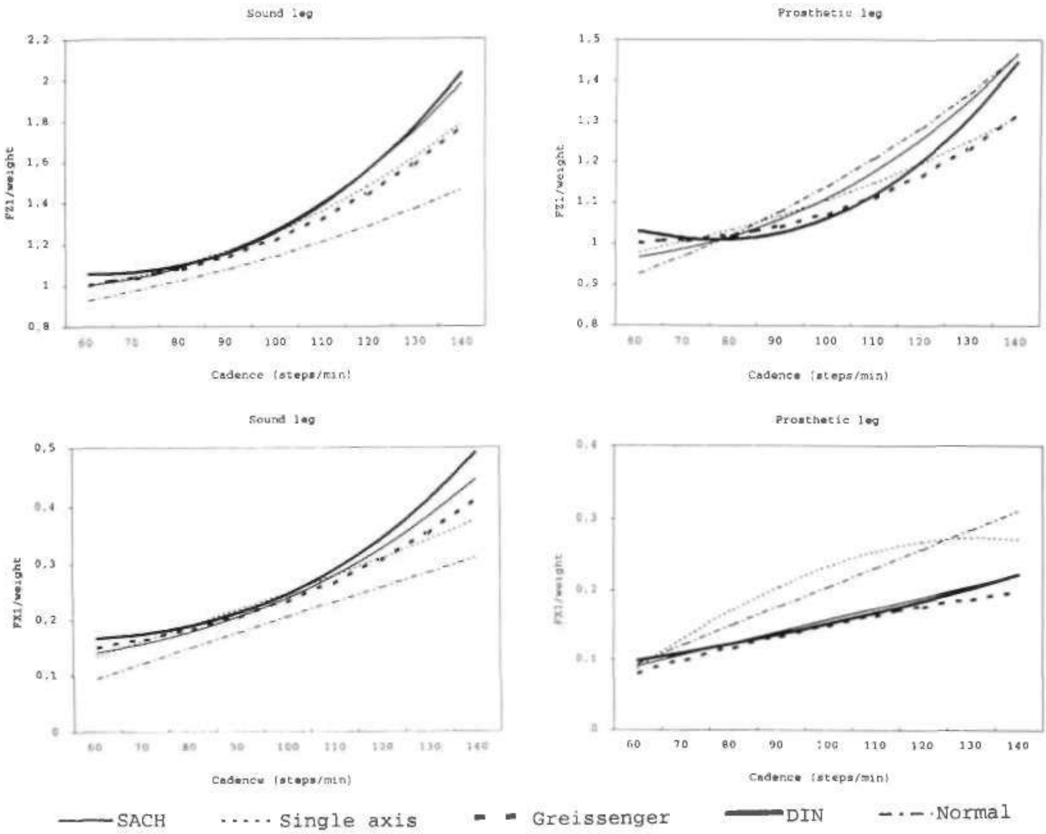

Fig. 3. FZ1 and FX1 quantitative curves as a function of cadence for each type of artificial foot in sound and prosthetic leg

prosthetic mechanisms, and even higher than for the control group. A possible explanation is that part of the energy used during gait causes the mechanism to extend (plantarflexion), which implies that it must pivot on/around the heel and means a greater braking force. Enoka *et al.* (1982) showed that this does not occur in the Greissinger foot, probably because a higher force is needed to perform plantarflexion, which in practice behaves as a non-articulated mechanism.

Conclusions

In summary, the general conclusions of the study are as follows:

- The method presented for the study of prosthetic gait seems to be appropriate because it is objective and quantitative, allowing comparison of the results obtained with different prostheses. It could be a valid proposal as a standard method for the study of prosthetic gait.
- The factors which influence the amputee's gait can be arranged according to the following order of importance: cadence and type of limb (sound or prosthetic): subject (which accounts for individual variability) and type of prosthetic mechanism used.
- Since these factors have a significant effect, they should be considered in the experimental design; otherwise, the conclusions attained can be confusing or mistaken.
- The results of this work show similarities between the kinetic behaviour of SACH and Dynamic feet on the one hand, and Single-axis and Greissinger on the other, This fact supports the criterion for the classification of prosthetic mechanisms as articulated and non-articulated.

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