University of Strathclyde
GLASGOW

Swing phase and its Control in the Trans-Femoral Amputee

by

Caroline Stewart

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Bioengineering Unit

Bioengineering Unit September 1995

THE CHARACTERIZATION OF SWING PHASE CONTROL UNITS FOR TRANS-FEMORAL AMPUTEES

STEWART CJ, ZAHEDI S*, SPENCE WD & SOLOMONIDIS SE

University of Strathclyde, Glasgow, Scotland
*Chas A Blatchford & Sons Ltd, Basingstoke

INTRODUCTION

A study of the effectiveness of swing phase control units for trans-femoral amputees is currently being undertaken at the University of Strathclyde. Six amputees have each spent 12 weeks wearing prostheses incorporating various swing phase control units. These included hydraulic (Catech) and pneumatic (Blatchford) cylinders and the Blatchford 'Intelligent Prosthesis' (IP). A number of questions has arisen.

1. What is the best method of evaluating swing phase control units?

This presentation seeks to explore the usefulness of data collected on a mechanical test machine in explaining phenomena observed in the gait laboratory.

2. What is the most meaningful way of specifying swing phase unit characteristics?

A swing phase control unit seeks to control the trajectory of the swinging limb by applying loads at the knee. The relationship between the load and the resulting kinematics is traditionally expressed using plots of moment against angle. The moment is, however, a combination of the force in the unit and the geometry of the prosthesis.

3. How can the action of swing phase units be ranked according to effectiveness?

The example given is a comparison of the performance of a hydraulic unit, the IP unit with the needle valve fixed and the IP unit with the processor changing the valve setting.

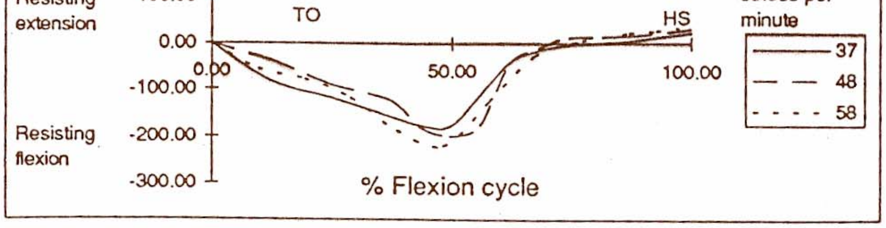
METHODS

One amputee was selected who had already completed trial periods with the three swing phase control units. Full 3D gait analysis had been performed in the motion analysis laboratory and the subject's observations recorded.

Units, tuned for his gait, were tested at Blatchford R&D laboratory. The tests used a variable speed motor to rotate a cam and impose stroke displacements on the units, simulating those experienced in gait. The IP unit with the needle valve fixed, is equivalent to a conventional pneumatic cylinder. It was tested, as was the hydraulic unit, at frequencies equivalent to slow, medium and fast gait speeds (c. 0.8-1.6m/s). The IP unit was then tested, with the processor changing the needle valve setting, at speeds corresponding to each of the five valve settings, already programmed for the amputee.

The resistance of the units was measured using a force transducer. The results over the period of simulated flexion are given. In each case the force returned to zero during the subsequent rest period, simulating fixed knee flexion during stance phase.

RESULTS



University of Strathclyde
GLASGOW

Swing phase and its Control in the Trans-Femoral Amputee

by

Caroline Stewart

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Bioengineering Unit

Bioengineering Unit September 1995

ABSTRACT

It is desirable that the trans-femoral prosthesis provides the support, power, control and feedback supplied by the musculoskeletal and nervous systems prior to amputation. The knee should bear load without collapsing into flexion in stance and control flexion during swing, for which the swing phase control unit is responsible.

The simplest units use friction brakes and springs. Hydraulic and pneumatic units employ the fluid properties of oil and air for greater control as walking speed changes. In 1993 Chas A Blatchford & Sons Ltd launched the 'Intelligent Prosthesis' (IP), introducing a microprocessor to control the flexion resistance valve setting according to walking speed and motivating this study.

In this project, the kinetics and kinematics of gait were determined using a Vicon system and Kistler force platforms. Six normal subjects were tested first. Six amputees were then recruited. Pneumatic, hydraulic and IP units were each tested at the start and finish of a 12 week continuous test period for each subject. Subjective feedback was recorded. Free knee, locked knee and extension bias units were tested in a single session.

To complement the gait analysis approach, a computer simulation of a swinging limb was constructed.

Significant differences were found between different swing phase control units. The pneumatic unit was generally satisfactory, but functioned less well at slow speed. The slow speed setting of the IP unit was effective and popular. The fast speed setting of the IP and the overall performance of the hydraulic offered some improvement in the kinematics but increased loads / powers. The free and extension bias units gave unacceptable kinematics. The locked knee required high hip moments to control swing.

The simulation model proved effective and useful, casting light on the influence of mass properties and initial swing kinematics and predicting the effects of design changes.

CHAPTER 10 FINAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

All the following discussion applies to gait at uniform speed, on a level surface, under laboratory conditions.

- **The Pneumatic Unit**

The pneumatic unit was described by the amputees as being satisfactory, predictable and controllable. Familiarity may have increased its acceptance as 4 of the amputees had used the pneumatic prior to the study. There were few criticisms but walking slowly caused some difficulty.

Amputees walked with the same normal walking speed as for the IP unit, which was faster than with the hydraulic unit, but the range of walking speeds offered was lower than with the IP.

The pneumatic unit generally gave the poorest control of swing phase hip and knee angles across the speed range. This results from the knee moment supplied by the unit. The moment resisting flexion decreases as walking speed increases, exactly the opposite of what is required. The result reflects in the swing phase hip moment parameters, which are lower than those for the other two units when walking quickly and higher when walking slowly. This explains the difficulty experienced by the amputees when walking slowly and the overall poorer speed control.

Examination of the contralateral limb shows some benefits of the pneumatic unit over the other two. The mean magnitude of the ankle moment, the peak moment from the knee flexors and the stance phase knee flexion angle are all lower. The lower knee flexion angle makes the gait style closer to that of normal subjects and the reduction in the moment from the knee flexors is especially important as this moment is much greater for amputees than for normal subjects.

The standard deviation of the velocity of the hip joint in the direction of progression is lowest, therefore most normal, reflecting a smooth forwards progression.

- **The Hydraulic Unit**

Most of the criticisms levelled at the hydraulic unit relate to its higher stiffness. Initiating swing phase flexion was more difficult and the prosthesis was less manoeuvrable. Walking was more difficult overall and demanded more effort. Changing and controlling speed also caused problems, placing a limit on the fast end of the range of walking speeds and walking slowly proved difficult. Gait style deteriorated and uncertainty increased concerning the timing of full extension. Two subjects felt that the swing was smoother.

The unpopularity of the unit was reflected in a lower normal walking speed and a reduction in the range of speeds offered.

The swing phase knee angle parameters for the IP unit are closer to those for normal subjects than those of the other two units. Especially marked is the improvement in the control of the timing of terminal impact as walking speed changes, as noticed in the subject feedback. The control of maximum knee flexion also improves, but less dramatically. This suggests that the unit has been tuned to control terminal impact time rather than heel height. The improvement in the knee angle control is reflected, to some extent, in the control of hip angle. There is not, however, a universal improvement in the kinematics as the thigh angular velocity and acceleration, already high for amputees, are highest for the IP unit.

The improvement in the angle control with walking speed comes from the greater speed dependency of the knee moment supplied by the IP swing phase control unit. The swing phase control unit forces measured using the test rig are also more speed dependent. The peak force increases with cycle frequency but the force at low knee flexion angles remains low, avoiding the difficulties observed with the hydraulic unit.

At the initiation of knee flexion, the IP unit absorbs the least power of the three units for slow speed walking and the hip power demand at slow speed is also the lowest. There is some evidence that the lower slow speed knee moment leads to a lower hip moment. The moment and power reduction explains the popularity of the slow speed setting and the ease of walking slowly. When walking quickly, however, there is a cost attached to the enhanced control. For normal and fast walking speeds, the power demanded of the hip musculature to initiate knee flexion is higher than for the pneumatic unit. At the same time power absorbed by the knee units for fast walking is greatest for the IP unit.

Considering the contralateral limb, the IP unit demands the greatest mean magnitude of the moment at the ankle. The mean magnitude of the moment at the hip is, however, lower than for the pneumatic or hydraulic units. There is also some evidence of a reduction in hip power. At the knee, fast walking demands a greater peak moment from the knee extensors than with other two units. This again illustrates the cost of control, as does the high knee power required for normal and fast walking. The peak moment of the knee flexors is the greatest, for the IP unit, across the speed range. This increased demand on the knee muscles of concern as knee moments are generally higher for amputees.

The ranges of motion at the contralateral hip and knee during stance phase are greatest for the IP unit and are therefore the most abnormal. The high stance phase knee flexion angle excursion probably accounts for the increased loads described above. The IP unit also gave the greatest standard deviation in the sound hip velocity in the direction of progression and the least in the medio-lateral direction. Both these trends increase the differences compared with normal gait.

flexors contract most powerfully and the amputee establishes the initial conditions of swing which will determine the later trajectory of the limb. This suggests that the IP unit is correct in applying control to the flexion rather than extension resistance valve.

2. The conflict between optimising kinematics and loads/powers emerged in the study. The improved kinematics at the initiation of knee flexion with the hydraulic unit and the enhanced fast speed control of the IP unit increase loads and powers. For the active amputee closeness to normal kinematics may be desirable. For a less active individual there may have to be a compromise.
3. The low significance of the differences between knee units from the ground reaction force parameters illustrates the effects of compensation and the need for full, 3D gait analysis.
4. The sound knee plays a major role in compensating for the prosthesis. Here the most elevated moments were observed and the stance phase knee flexion angle increased. The increase in load on the contralateral limb with increasing walking speed was very apparent, especially at the knee. As walking speed increases the need for compensation increases.
5. There were changes in the amputees' gait over the test period. This demonstrates the need for long term studies.

- **The simulation model**

1. Simulation is feasible and useful. The direct dynamics approach is most powerfully used in combination with the inverse dynamics approach of gait analysis.
2. The laboratory situation can be reproduced using simulation.
3. Freely swinging limbs demonstrated the need for controlling moments during swing phase. It was also demonstrated that, in general, bringing the mass properties of the prosthetic shank closer to those of the normal shank improved the swing trajectory.
4. The advantages and disadvantages of small design changes to the IP, hydraulic and pneumatic units were demonstrated.

- **Recommendations for future work**

1. This study has focused on the sagittal plane and the legs. Further study is required of the kinetics and kinematics of the trunk, pelvis and arms and of the whole body in the frontal and transverse planes.
2. The initiation of swing phase has been shown to be of particular interest. There is room for further investigation here and the simulation model should be expanded to cover this phase.
3. Significant changes were observed in the parameters examined between the start and finish of the test period. These changes require further investigation, quantification and explanation.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor, Mr SE Solomonidis, for his encouragement, support and advice throughout the project.

I would like to thank Mr WD Spence for his contribution to the project, especially for the many hours spent in the laboratory, for his comments and for keeping the test programme running smoothly.

I am grateful to Mr S Murray for assembling and re-assembling all the prostheses, often to fit in with a tight schedule.

Especial thanks go to the 12 volunteers in the study, particularly the amputees, who spent many hours walking up and down the laboratory. I appreciated the willingness of the amputees to try different swing phase control units and found their feedback very valuable.

I would like to thank Prof J Paul for the hours he spent reading draft copies of this thesis, for his suggestions, ideas, corrections and availability for discussion.

I am particularly grateful for the collaboration of Chas. A Blatchford & Sons Ltd., especially the assistance and advice of Mr S Zahedi.

Support from Prof Barbenel and the staff of the Bioengineering Unit has been invaluable. I am particularly grateful to Mrs S Nicol, Dr A Nicol and the technical staff.

I would like to acknowledge the assistance I received from the staff of the computer centre, the National Centre Library and the departments of Mathematics and Statistics and Modelling Science.

I have enjoyed the friendship and assistance of my fellow students and the opportunities for discussion. I am particularly grateful to Miss A Fitzsimmons for her co-operation and ideas.

I would like to acknowledge the financial support of the EPSRC in providing my grant and Chas A Blatchford & Sons Ltd for the prostheses and subject expenses.

I will always be grateful for the love and support of my family and the care and faithfulness of my friends.