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The Analysis, Design and Implementation of a Model of an Exoskeleton to Support Mobility

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Abstract - *The potential for using an exoskeleton to support mobility has been considered for some time. The paper describes the procedures associated with the analysis, design and implementation of a model for a lightweight design of such an exoskeleton and shows how the integration of motion analysis with modelling supported the development of the concept. It then proceeds to consider the implementation of the identified control and operational strategies in model form and how the basic concepts developed are being deployed in support of an implementation of system to support the rehabilitation of the lower limbs.*

I. Introduction

NONE trauma based lower limb disabilities can be broadly categorised as resulting from either a nerve-based disease or a muscular-based disease, though most of the conditions that express such disabilities are in fact a mix of both forms within the mapping of such illnesses. One of the key areas of support for individuals with lower limb disabilities, whether resulting from trauma or disease, is that of providing, and enhancing, mobility, something which is currently achieved largely through the use of wheelchairs. However, there is a case to be made for some of these individuals to attempt to restore, either in whole or in part, a degree of the Walking Function.

In animals locomotion is usually achieved by means of articulated limbs, this is sometimes referred in the literature as Articulated Locomotion [1] with a variation in energy requirements due to size constraints between groups of animals. The bigger the animal the less number of actuators it can afford to power. There is also a computational issue as the musculo-skeletal systems of most mammals boast a few hundred Degrees of Freedom (DoF) [2].

In machine aided bipedal walking, the control of the system is a critical factor and the following must be taken into account [1]:

- Control of limbs is of synchronic nature.
- Control of positioning and acceleration is required for the limbs.
- Stability can be achieved by means of controlling the position of the Centre of Gravity.
- Control strategies must adapt to the environment.
- Optimum control of energy requirements must be achieved.

In humans, the motion control system may be considered in relation to the brainstem-spinal system, the limbic system and the neocortex [1]. Early projects aimed at rehabilitation include those at the Mihailo Pupin Institute in Belgrade [2] [3], at the University of Winsconsin [4] and at the Tokushima Hospital in Japan [2] in the early 1970s. More recently, work such as that at the University of Tsukuba [5], the Kanagawa Institute of Technology [6] and Berkeley [7] have attempted to provide powered augmentation of the walking function.

None of these systems however met the requirements of an effective support for the walking function in a simple, lightweight system which could provide limited support for mobility in constrained environments such as a supermarket or a museum. The project as described therefore took as its premise a requirement for a system to support the walking function for a limited period of time in such environments while retaining the wheelchair as the primary means of achieving mobility.

II. Gait Analysis and System Modelling

The starting point for the development of the exoskeleton was to gain an understanding of the requirements of achieving a natural gait using information such as that shown in Fig. 1, derived from a gait analysis system. The information derived from this enabled a series of dynamic models to be produced using the Visual Nastran kinematic modelling package which emulated various gait patterns and enabled the visualisation of different operational strategies [8]. This was supported by the use of models such as that shown in Fig. 2 where the basic dynamics of the gait were able to be visualised through various types of motion and or a range of user dimensions.

Working from the basis of the models, a decision was made to base the exoskeleton around the use of a linear actuator and to use crutches to provide additional support during both the stance and swing phases of the gait. The relationship between the system model and the underlying biomechanics can be seen from Fig. 3 in which Zefran's model for walking with crutches [9] is presented along with the Virtual Nastran model derived from this and incorporating the linear actuators used to lift the foot clear of

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the ground during the swing phase. These models hen formed the basis for determining how the operation of the actuators could be integrated with the 4-point walking patterns identified by Zefran [9]. These patterns are referred to as the ipsilateral and contralateral gait patterns and are as shown in Fig. 4.

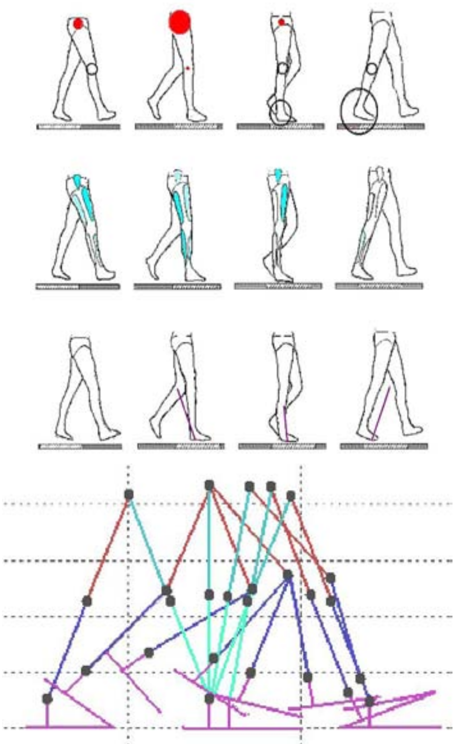


Fig. 1. Simulation of a full step with GaitLab showing the profile for joint and muscle activity and ground forces and simulation of a full step using MatLab

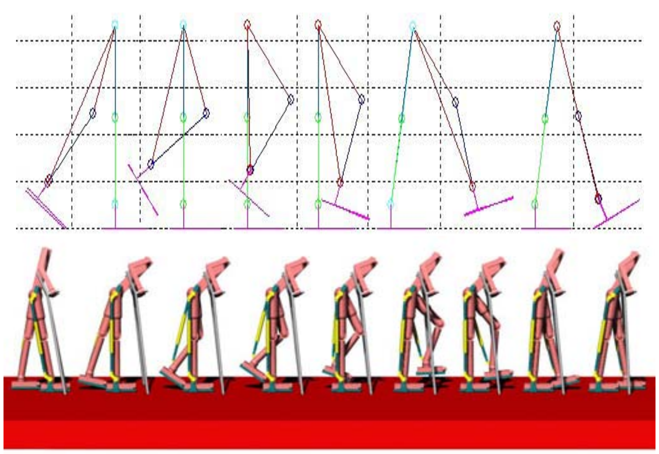


Fig. 2. Simulation of a full step for the exoskeleton using MatLab and Visual Nastran

A. Walking with Crutches

The decision to use crutches to provided additional support during the stance and swing phases also impacted upon the operation of the system controller as the question of maintaining stability during the single point support phase experienced in normal walking was removed. This had the effect of simplifying the control strategy and enabled the user to both initiate and control an individual step via controls built-in to the crutch handles.

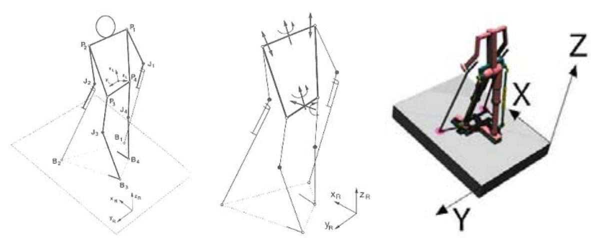
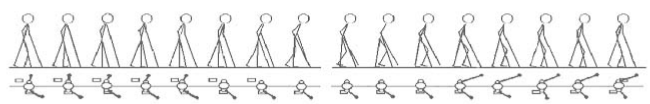
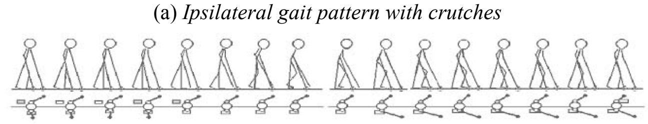


Fig. 3. Zefran's model with flexible trunk [9] and Visual Nastran model of walking with crutches



(a) *Ipsilateral gait pattern with crutches*



(b) *Contralateral gait pattern with crutches*

Fig. 4. Gait patterns when walking with crutches (after Zefran)

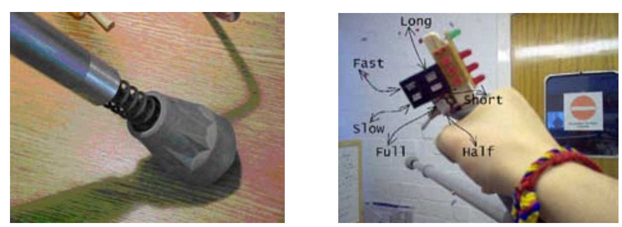


Fig. 5. Crutch sensor showing variable rate spring and controls on the handle of the crutch

In operation therefore the system would first seek to determine if a stable 4-point stance had been achieved. This is done by means of pressure sensors in the soles of the user's shoes together with a simple sensor, shown in Fig. 5, which detects the presence of a downward load at each crutch. Once a full 4-point stance is established, the user is then free to initiate the step. The controls on the crutch enabled the user to select one of eight step profiles based around the stored settings for step length, step interval and

TABLE 1
SELECTABLE STEP PROFILES FOR EXOSKELETON

	Step Length		**Step Length**	
	Long	**Short**	**Long**	**Short**
Step Interval = Fast	Profile 1	Profile 2	Profile 5	Profile 6
Step Interval = Slow	Profile 3	Profile 4	Profile 7	Profile 8
	Profiles for Step Height = **Full**		Profiles for Step Height = **Half**	

step height as set out in Table 1. For users with control of their hip muscles, and hence of the time and length of the swing phase they would simply select the step height.

B. *Energy Requirements*

As the main function of the exoskeleton was that of lifting the leg and controlling the position of the ankle during the swing phase, the energy requirements could be kept to a minimum. The lifting of the leg could be translated into that of lifting a mass from 10 to 15 kg through a distance of 20 to 40 cm, requiring a maximum force of the order of 150 N.

C. *Controller*

The fact that the exoskeleton was responsible for the lifting the leg also simplified the control requirements, meaning in essence that the emphasis could be placed on position and detecting contact with the ground at the end of the step. Balance would then be controlled by the user with the aid of the crutches.

(a) *Simulation*

(b) *Functional model*

Fig. 6. Quarter-scale rig in laboratory

III. System Demonstrator

In order to prove the systems concepts it was not possible in the development stage of the project to put in place a full size exoskeleton so a laboratory system was modeled and produced. This was then linked to the instrumented crutches to demonstrate the motion profile and to enable an evaluation of the user controls embedded in the handles of the crutches. Figure 6a shows the simulation of the quarter-scale model together with the predicted tracks for the ‘knee’ and ‘ankle’ which could then be compared with the tracks generated by the functional model of Fig. 6b. Figure 7 then shows the elements of this rig.

Once the functional model of Fig. 6(b) was available it became possible to use a motion capture strategy based on the use of video imaging to compare the predicted motion of the exoskeleton, and shown in Fig. 6(a) with the achieved motion derived from the system controller as defined by Fig. 7.

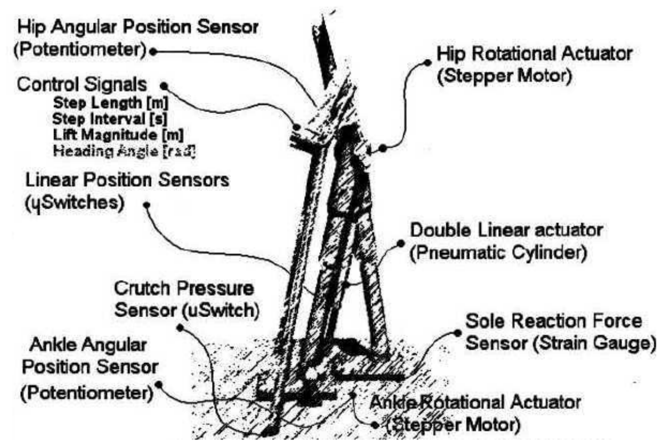


Fig. 7. System mapping for quarter-scale rig

Using this approach, results from which are shown in Fig. 8, it was possible to verify that the controller provided the required form of motion. The main discrepancy between the predicted motion and that achieved was associated with the control of the position of the ankle during a step. This can be seen from the image analysis derived curve of Fig. 9 which shows the track of an individual walking normally without crutches as derived from video capture and the track of the ankle used on the model. The variation resulted from the fact that although the aim was to reproduce a natural gait, it was however found that with the exoskeleton, in order to improve toe clearance during a stride, it was necessary to maintain the contraction of the linear actuator for a greater part of the swing period.

If crutches are now added then the observed gate is as shown in Fig. 9 in which it is seen that the track of the ankle is even lower than for normal walking. Again necessitating the longer retraction of the actuator on the exoskeleton.

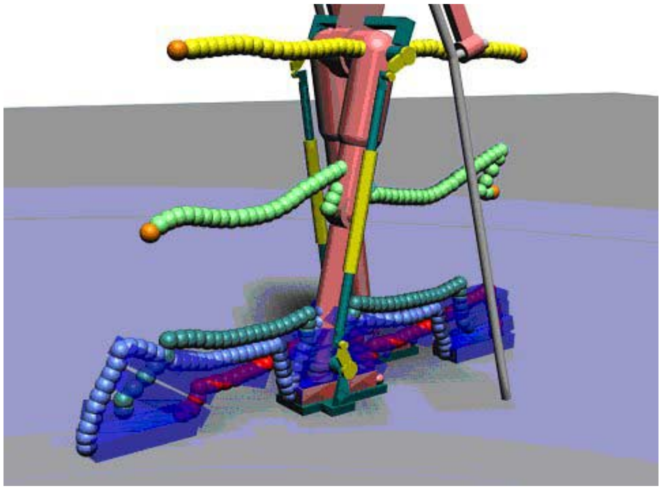


Fig. 8. Model studies shown tracks developed for the motion of the hip, knee, ankle, toe and heel during a single step

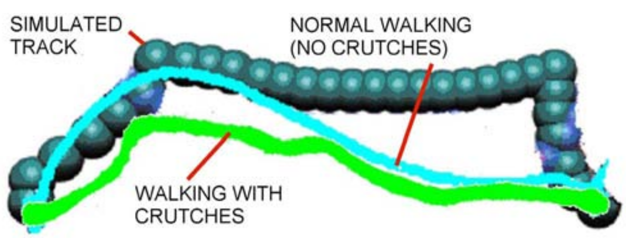


Fig.9. Variation in ankle position during walking with and without crutches compared with ankle track developed for the model

IV. Rehabilitation of the Lower Limbs – The N*e*XOS Project

Having developed the basic concept of the exoskeleton, consideration had to be given as to how to progress its development. Following a formal evaluation of the system, two options presented themselves; to continue to work towards a full scale version of the exoskeleton or to develop the concept as a rehabilitation aid. Discussions with physiotherapists and rehabilitation specialists led to the latter approach being adopted and the exoskeleton then formed the basis of the N*e*XOS project which began in 2003 [10].

The initial concept of the NeXOS project was to use the exoskeleton concept of a 'linear knee' to help and support physiotherapists in working on the rehabilitation of the lower limbs of individuals with a wide range of conditions. However, work with physiotherapists to establish their needs and requirements has resulted in an evolution of this initial concept towards a geometry which increases the flexibility of the system while providing an increased range of movement beyond that capable of being achieved by the basic exoskeleton. This translation of the original concept has however served to illustrate the need for design flexibility to meet a wide range of needs from a common starting point.

V. Conclusions

The paper discusses the concept of a lightweight exoskeletal system to support increased and enhanced mobility for individuals with lower limb disabilities, whether resulting from trauma or disease. The system utilises inputs from the user by means of controls embedded in crutches to provide a range of step profiles. This concept has been tested in the laboratory by means of a quarter-scale model with video capture methods being used to compare real walking with and without crutches with the derived motion of the exoskeleton.

Following the development of this model, and following discussions with healthcare practitioners, the concept of the exoskeleton has evolved in the first instance not as an aid to walking, but as a means of providing support for physiotherapists in relation to the rehabilitation of the lower limbs. This latter application is currently being developed and a prototype system is targeted to be with physiotherapists in mid-2005.

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