

Real time description of lower limb motion for nonanalytical neuroprosthetic control applications

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Abstract

Finite state models of locomotion are often used to incorporate biomechanical knowledge of gait into lower limb neuroprosthetic control systems. The models are typically derived from the contributions of experts in gait biomechanics and rehabilitation technology. The resulting gait patterns can be used to derive stimulation strategies to help restore motor function. Human gait is probably the most studied of human motions, however considerable problems remain in deriving applicable finite state models of gait. This is partly due the low number of invariant gait characteristics that can be reliably identified in real time. This paper presents a novel method for the finite state modelling of lower limb motion by coding limb segment interactions (CLSI). Angular velocities of limb segments are used to derive a binary code representative of invariant states of locomotion. The method is illustrated using a normative gait record. The resulting code demonstrates that knee flexion and extension phases of gait can be identified in real time in terms of the rotational interactions of the thigh and shank segments. The hardware elements required to derive the code in real time are presented. The application and potential of CSLI coding strategies for the synthesis of nonanalytical neuroprosthetic control systems is discussed.

1 Introduction

Non analytical methods of motor control have been adopted for a multitude of FES applications to help improve walking function in individuals with neuromotor pathologies. The method is attractive due to the simple heuristic representation of relatively complex motor control problems and solutions. The method requires the abstraction of both plant dynamics and control solutions into finite automata systems. Finite state controllers are

able to regulate the execution of control responses according to identifiable phases of gait. Control architecture is typically hierarchical with higher coordination and lower actuator levels of control. Significant problems remain in deriving adequate muscle actuator levels of control, however these will not be discussed here. This paper pertains to the coordination level of control, and in particular to the real time acquisition and finite state representation of lower limb motion. Extensive knowledge of gait biomechanics is available, however synthesis of the coordination control level remains difficult due to a low number of invariant gait phases that can be reliably identified in real time. This is due to the current limitations of sensor technologies and methods of signal interpretation. Various sensor combinations have been proposed for lower limb FES applications [1][2]. Many are able to determine functional phases of gait such as loading response, mid stance, pre-swing and swing. However these systems are not able to describe limb motion in a systematic and continuous manner throughout the entire gait cycle. Impaired knee function with foot drop is commonly seen in hemiplegic patients. An automated method for the real time description of knee motion may be helpful in deriving control schemes to coordinate the stimulation of multiple muscle groups in order to improve knee function.

2 Methods

Finite state modelling of locomotion is achieved by abstracting a simplified description of gait biomechanics. This is done in terms of invariant sensory states which pertain to different phases of gait. In this paper we will consider the invariant representation of lower limb motion, in particular the thigh and shank segments and their contribution to knee joint motion. Lower limbs can be modelled as an inverse pendulum chain with anatomical constraints restricting the range of possible

rotation. Limb segment motion exists in three planes here we will only consider motion in the sagittal plane. While flexion and extension may be joint outcome states, it is conceivable that opposing joint segments may achieve these two states through different rotational interactions. The opposing joint segments can rotate in combinations of either (positive) counter clockwise (CCW) or (negative) clockwise (CW) directions. Directions of rotation are easily detected by examining the sign of segment angular velocities.

Consider knee joint extension and flexion phases. Joint extension may be achieved by segments rotating in opposite directions, the thigh clockwise (CW) relative to the hip and the shank counter clockwise (CCW) relative to the knee. From this perspective view the opposite segment rotations (thigh CCW, shank CW) would result in joint flexion. However two invalid interactions exist. Extension cannot occur with the thigh rotating counter clockwise (CCW) and the shank rotating clockwise (CW). Similarly flexion cannot exist with the thigh rotating clockwise (CW) and the shank rotating counter clockwise (CCW). Flexion and extension states are also possible with the segments rotating in the same direction but with one segment rotating faster than the other. The resulting six possible joint interactions are illustrated in figure 1.

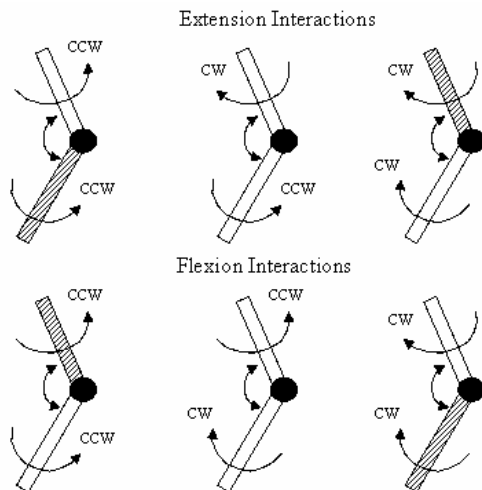


Figure 1:
CW-Clockwise, CCW-Counter Clockwise
Faster segments shown shaded

These interactions can be determined and represented in real time using a system of comparators, which can determine directions of

rotation as well as compare the respective segment angular velocities. The interactions can be represented in the form of a 3-bit Binary word an example of which is shown in figure 2. The MSB denotes overall joint flexion/extension, the remaining bit and LSB denoting the directions of rotation for the thigh and shank segments respectively. The binary representation can be extended further by adding an extra bit to describe joint angular acceleration as shown in figure 3. However relative joint angular velocity is a bipolar signal, as such the resulting acceleration joint state must be considered appropriately in terms of joint flexion and extension.

Joint State	Bit 3 (MSB)	Bit 2		Bit 1 (LSB)	
		Thigh Direction		Shank Direction	
		CW	CCW	CW	CCW
Flexion	1	0*	1	0	1*
Extension	0	0	1*	0*	1

Figure 2:
3-bit CLSI Binary Assignments
*Invalid Interactions

Joint State	Bit 4 (MSB)	Bit 3		Bit 2		Bit 1 (LSB)	
		Thigh Direction		Shank Direction		Joint Acceleration	
		CW	CCW	CW	CCW	Accelerating	Decelerating
Flexion	1	0*	1	0	1*	1	0
Extension	0	0	1*	0*	1	0	1

Figure 3:
4-bit CLSI Binary Assignments
*Invalid Interactions

3 Results

The CLSI method applied to a normative gait record is presented in figure 4. Flexion and extension joint states can be readily identified by code values above or below 4 respectively in the case of 3 bit CLSI, and similarly above or below 8 in the case of 4 bit CLSI. At initial contact (IC) the knee is shown to be in a state of flexion, the mechanical coupling between segments results in a change in joint angular acceleration, observable as a local maximum in the joint angular velocity record and detected in the 4 bit CLSI. The body is then propelled forward as the knee proceeds into extension with both the thigh and shank segments rotating clockwise. During the latter stages of stance, as the knee flexes, the thigh rotational direction changes from clockwise to counter clockwise. Swing phase is initiated at toe off (TO). As the limb is lifted the shank rotation (CCW) begins decelerating. This can be observed as a local

maximum within the joint angular velocity record and is also recorded in the 4 bit CLSI. A small period of swing flexion occurs to aid foot clearance. The shank then changes direction until the end of swing flexion is reached. Swing extension occurs with both the shank and thigh segments rotating counter clockwise. Swing extension ends just prior to heel strike.

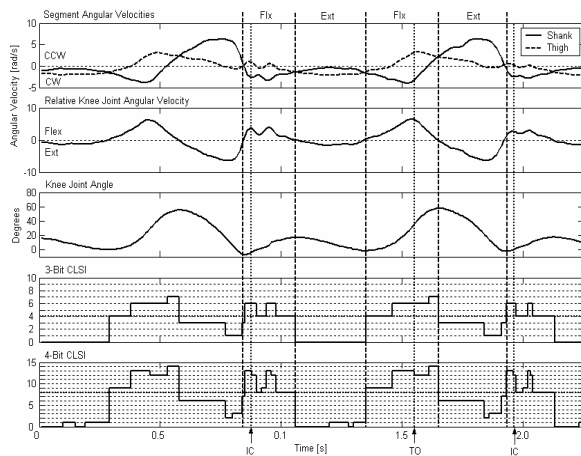


Figure 4:
IC-Initial Contact, TO- Toe Off, CW-Clockwise,
CCW-Counter Clockwise, Flx-Flexion, Ext-
Extension

4 Discussion and Conclusions

The resulting CLSI descriptions are comparable to previously published descriptions of gait [3]. The interpretation of motion is not specific to any one type of activity, and it is therefore tempting to speculate that the CSLI method may be useful for analysing other walking motions. The CLSI strategies presented compare favourably with previous finite state modelling strategies [4][5] as more states can be abstracted. Adopting non analytical methods of motor control is computationally less demanding than other classical control methods, however identifying gait characteristics is still required. Human gait appears as repeating patterns of oscillatory trajectories, we therefore conclude that it is not inappropriate to describe gait patterns in terms of angular velocity and acceleration. The CLSI code transitions are detectable in real time, directly descriptive of kinematical changes and are therefore useful for the planning of motion executions. The CLSI method results in a binary code which can be easily interfaced with ancillary control hardware. It is conceivable that a controller would be able to identify

perturbations from a built in knowledge of CLSI code sequences and transition timings, which may be of value in the synthesis of neuroprosthetic control systems.

In this paper we describe an automated method for the real time description of limb motion. It must be admitted that practical implementation of the CLSI method depends on the both the suitability and availability of sensors. Following from our previous work evaluating the potential of miniature piezoelectric gyroscopes as a sensor for the FES correction of foot drop [6][7], we are investigating the potential of the gyroscope for the practical implementation of CLSI. The simplicity of the CLSI method and its potential for nonanalytical motor control systems seems to offer encouragement for further work in this area.

References

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