DEVELOPMENT OF A BIOMECHANICAL MOTION SENSORIMOTOR PLATFORM FOR ENHANCED LOCOMOTION UNDER MICROGRAVITY CONDITIONS

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ABSTRACT

Motor-related tasks in microgravity conditions on the lunar surface can be difficult and physiologically compromising. Current prosthetic systems use electromyography (EMG)-based techniques for creating functional sensorimotor platforms. However, novel prosthetic accelerometer technology has been identified and may be used to restore normal movements under these conditions. Here, we describe the development and proof-of-concept for a biomechanical sensorimotor platform that makes use of this technology to promote enhanced locomotor activity under microgravity conditions. Future avenues should focus on the validation of this model and practical considerations for its implementation in orbit and/or lunar surfaces.

1 INTRODUCTION

For humans accustomed to 1-G environments on Earth, microgravity conditions in orbit and on celestial bodies with lower gravitational field, such as the Moon, can be physiologically compromising. Of these, motor and fine-dexterity tasks involving the extremities, particularly in locomotion, grasp and release, are influenced becoming delayed and placing greater force demands [1]. With the accelerating pace of prosthesis developments, research has reached frontiers in the development of biomechanical systems providing both sensory and motor feedback platforms to the user [2,3]. Our group has recently developed an advanced model incorporating a sensorimotor platform that integrates sensing accelerometers with additional enhancements for use in prosthetic systems and performed simulations to test its efficacy [4]. The authors hereby propose incorporating this same technological innovation into loading suits and considerations for its design in orbit or celestial environments with under microgravity conditions.

2 BIOMECHANICAL PROSTHESIS MODEL

Current prosthetic systems use electromyography (EMG)-based techniques for creating functional sensorimotor platforms. However, several limitations in practical use and signal detection have been identified in these systems [5,6]. Accelerometer-based sensorimotor systems have been suggested to overcome these limitations but only proof-of-concept has been demonstrated [2,6,7]. This alternate model utilizes a sensorimotor platform for upper limb prosthesis users using accelerometer sensing and controllers (Fig. 1).

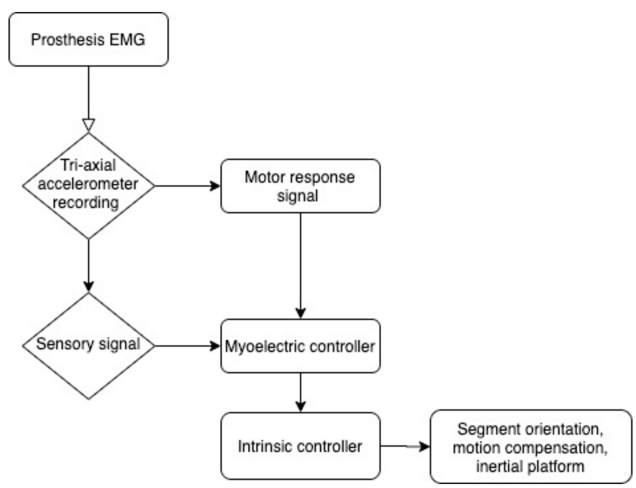

Figure 1: Tri-axial sensorimotor prosthesis model.

This model consists of tri-axial system, whereby sensors and controllers are employed to detect and correct for key motor control elements consisting of 1) segment orientation, 2) motion compensation, and 3) inertial platform (Fig. 2) [2,6]. Segment orientation is a compensatory mechanism for the accelerometer that takes into consideration the gravitational forces and tri-dimensional, spatial alignments in order to accommo-date the motor demand accordingly. Alternatively, motion compensation adapts for the positioning using the surrounding prosthetic limb segment kinematics. In addition, the inertial platform controller uses holistic, mathematical analysis of prosthesis in interaction with an object of interest.

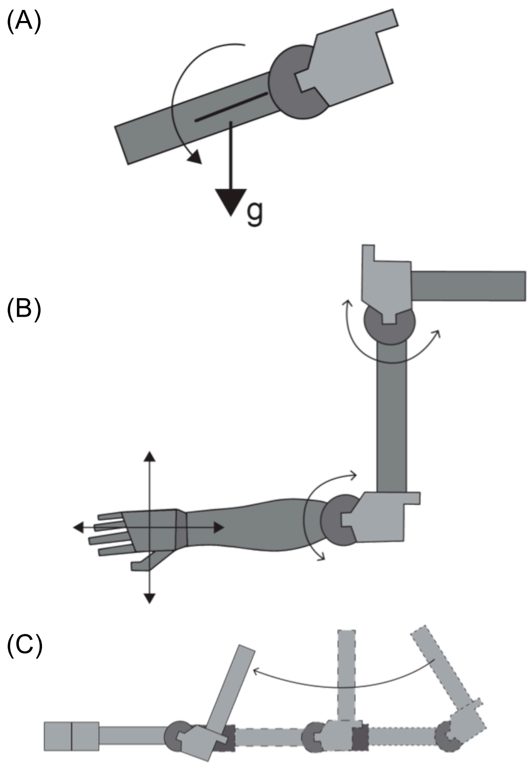

Figure 2: Modeled forms of locomotion compensation by tri-axial system: (A) segment orientation (B) motion compensation and (C) inertial platform. Adapted from Kyberd & Poulton [2].

3 SENSORIMOTOR PLATFORM DESIGN

It is possible to determine optimal design standards for various material properties for accelerometer sensor construction. This has previously been considered in our design of a prosthetic biomechanical sensorimotor platform and can be extended to creating the framework for loading suits. Determining optimal standards requires accounting for the following variables:

Q-factor: a measure of how under-damped an oscillator is. As all materials have a natural frequency of vibration, determining the Q-factor can be utilized to measure the dampening according to the construction material properties. If the Q-factor is too low, damping in the system will result in a reduced sensitivity. The Q-factor can be calculated by:

$$Q = \sqrt{(Mk)}/D \qquad (1)$$

where Q is the Q-factor, M is inertial mass, k is the spring constant, and D is the damping coefficient, where

$$k = (Ewt^3)/(4L^3) \qquad (2)$$

and

$$D = -F_{drag}/v \qquad (3)$$

where E is Young's Modulus, w is cantilever width, t is its thickness, and L is its length. In calculation of the damping coefficient, the drag force, F_{drag}, and velocity, v, and ultimately, the rigidity parameter are largely dependent on material properties. By this proof, a sensor design of higher sensitivity must utilize an optimized higher inertial mass, cantilever construction using a material with a higher spring constant.

Deflection: the degree to which a cantilever is displaced under a load. A higher deflection is typically an indicator of a higher cantilever design sensitivity [8]. The Stony Equation can be utilized to calculate deflection:

$$\delta = L^2 3\sigma(1\text{-}v)/Et^2 \qquad (4)$$

where δ is the cantilever deflection, L is the length of the cantilever beam, t is its thickness, σ represents the uniaxial stress or force per unit square, v is Poisson's ratio, and E is Young's modulus. Deflection is inversely proportional to the spring constant.

Stress: a measure of the internal forces resulting within a material system. Mechanical stress can be classified according to the type of forces acting on the system and include: scalar (tension or compression), bending, and torsional (shear) stress. In a cantilever beam system, the increasing the structural load, M, notably increases levels of bending and shearing stress.

Strain: a measure of stretch or deformation that occur as a result of mechanical stress. Strain occurs when a force is applied to an object and results in a physical change, whereas stress concerns only the forces regardless of any physical changes to the material. The resolution of measurements, quantifiable by the Q-factor, and deflection levels, rely essentially on both of these parameters. This is demonstrated mathematically by the Young's modulus ratio and its presence as a variable in calculations for the spring constant (ultimately, Q-factor) and deflection:

$$E = \sigma/\varepsilon \qquad (5)$$

where σ is the uniaxial stress, determined as a pressure or force per square unit, and ε is the strain, which is a dimensionless quantity representing the proportion of deformation. Based on optimization used in the design of multi-DOF robotic arms in varying gravitational fields to enhance load bearing [9], it is possible to describe optimal vibration frequencies and strain magnitudes. Both stress and strain therefore influence the overall resolution of measurements and must be considered in the design.

4 LOADING SUIT INCORPORATION

We suggest the combined application of prosthetic accelerometers in loading suits and EMGs for input signal detection, quantification, and predictive output modeling necessary for improved motion adjustments under microgravity conditions. Most clinical prosthetic require the use of compact elements that include drive systems, cells, and microprocessors for functional motion adjustment and response. Within drive systems, servo motors enable continuous monitoring of feedback signals and on-going adjustment of movement for any deviations detected. Additionally, these system elements must have appropriate interfaces and the ability to sustain constant activity for practical prosthesis.

In the case of locomotion in space conditions, gravitation is not expected to have an effect, as this model exploits the Equivalence Principle, which states forces due to gravity and acceleration are indistinct. In other words, the gravitational acceleration or otherwise lack of gravity would not affect this feedback system. In addition to this, previous results indicate this sensorimotor modal has an ability to reduce signal-noise effects observed in conventional accelerometer sensing platforms used in prosthetics. It demonstrates the possibility of signal enhancement and noise reduction through mechanical dampening of the system. It is additionally possible to optimize design variables to enhance sensitivity and upgrade accelerometer design specifications as needed. It is anticipated this technology can enhance tasks such as repairs or construction or perhaps in recreational design when considering commercial and private human access to space.

Moreover, the incorporation of a strain guage within the loading suit framework will offer increased safety and support with respect to microgravity-induced skeletal loss or wasting [9]. Physical exertion tasks, such as running, can produce peak strain magnitudes of 2000–3500 microstrains and the act of standing alone imposes strains in the optimal spectral range of 10–50 Hz. This incorporated guage represents an instrument that can permit astronauts to take part in exercise activities. As such, more robust extraterrestrial exercise programming could also be developed around this device following its incorporation within the suit's framework.

3.1 Limitations

Though conceivable, feasibility and a proof-of-concept must be demonstrated prior to implementation. Foreseeable limitations with this design include establishing a differential feedback transduction system design for non-prosthetic users and ergonomic considerations for loading suits. Additionally, surface EMGs are limited by signal noise, when compared to needle electrode and fine-wire EMGs, which are often classified as gold standards for signal detection for diagnostic purposes. Moreover, as EMGs are not the sole input in this model, complex multi-input variable modeling, an inherent part of biosensor feedback systems, cannot be avoided. There additionally exists the need to design this within currently costly loading suit designs, which may not be economical in the context of resources and costs, especially for large-scale space flights or missions.

5 CONCLUSION

The incorporation of a prosthetic biomechanical sensorimotor system in loading suits to enhance locomotion under microgravity conditions are conceivable; however, demonstration of a proof-of-concept is required before implementation.

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