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An Informational Algorithm as the Basis for Perception-Action Control of the Instantaneous Axes of the Knee

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Abstract

Traditional locomotion studies emphasize an optimization of the desired movement trajectories while ignoring sensory feedback. We propose an informational based theory that locomotion is neither triggered nor commanded but controlled. The basis for this control is the information derived from perceiving oneself in the world. Control therefore lies in the human-environment system. In order to test this hypothesis, we derived a mathematical foundation characterizing the energy that is required to perform a rotational twist, with small amplitude, of the instantaneous axes of the knee (IAK). We have found that the joint’s perception of the ground reaction force may be replaced by the co-perception of muscle activation with appropriate intensities. This approach generated an accurate comparison with known joint forces and appears appropriate in so far as predicting the effect on the knee when it is free to twist about the IAK.

Keywords: Instantaneous axes of the knee (IAK); Ball-Desteli diagram; Perception-action coupling manifold; Gibson’s theory of affordance; Ball’s screw theory; minimum information principle; Muscle synergies

Introduction

Berntein [1] recognized that effectors (feed-forward sensors) were not the only important components to movement; feedback was also necessary. It is clear that human locomotion may be studied from a number of different points of views (e.g., anatomical, biological, mechanical). Our interest here is in the control of skeletal activities, specifically, the stance phase of gait; when the leg is nearly fully extended and the foot is in contact with a reaction surface. Neptune used the optimization algorithm fine-tuned the muscle excitation patterns for each muscle group to produce a well-coordinated walking pattern that emulated the experimental data [2-4] however, in order to reduce the number of musculoskeletal degrees of freedom (DOFs) upon which the nervous system must operate, we have adopted the proposition that the nervous system controls muscle synergies, or groups of co-activated muscles, rather than individual muscles [5,6]. The muscle synergy is equivalent to the complex of lines, a manifold arrangement approximated by individual fibers (Figure 1).

Unique features of the muscular control system are not only in the biological nature of its actuators, but also the specific ways in which the control information is processed [7]. The sensorimotor information is transformed into control signals passing through neural networks. Traditional emphasis has been on optimizing desired movement trajectories while ignoring sensory feedback. Recent work [6] has redefined optimality in terms of feedback control laws, and focused on the mechanisms that generate behavior online. In the case of skeletal control, the internal mechanism describing ways in which the input information is transformed into the output for muscular activation, is lacking [8]. Understanding the complex interplay between neural circuits and biomechanics that give rise to muscle synergies will be crucial to advancing our understanding of neural control mechanisms for movement [5].

So far, two approaches in studying of the neuromuscular system have been used. Advances in electroencephalography have made it possible to study the correlation of different levels of neural system and muscular activity [9]. At the other extreme, the peripheral neuromuscular blocks, meaning the local organization of neurons, muscles, skeletal elements, and associated sense organs, has also been made the subject of several studies [10,11]. From a control engineering point of view, the models of peripheral block are derived basically by using the theory of servo mechanisms.

Figure 1: The fiber tractographic results of a portion of the gastrocnemius lateralis muscle generated in a healthy subject. The images were generated using the theory of servo mechanisms.

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The problem, however, of coordination of the different muscle groups involved in the repetitive sequence of skeletal activities, such as locomotion [12], has been given limited attention from the point of view of control theory when random effects [13] can arise in the control process. In fact, the skeleton with all its actuators represents a typical large control system. Therefore it is interesting to explore what result can be obtained by using a systematic approach to muscle control. In this article, we present the concept that control lies in the human-environment system which fits into an existing literature of ‘ecological psychology’.

Human movement control can be seen as a process that is distributed over the performer-environment system, i.e., rather than being localized in an internal structure within the performer [14]. A recent study [15] confirmed that leg stiffness is not directly related to running mechanics, but rather, to the running environment. Other studies also found that the stiffness of the leg might be altered by changing the activation of muscles acting about the joints of the leg [16,17]. The relationship between stiffness (vertical, leg and joint parameters) and running surfaces was studied using spring-mass system models [18-21].

The adjustability of leg stiffness may be important in allowing the body’s spring system to operate over the variety of terrain encountered in the natural world [22]. The performer and his/her environment (surface) may be said to be co-participants in any resulting action. In this way, actions are specific to function rather than to mechanism [23]. Movements and postures are controlled and coordinated to realize functionally specific acts that are themselves inseparable [24,25]. We have enunciated a principle, which applies to the reciprocal screw system and involves the theory of equilibrium that has freedom of the first order.

The term haptic perception refers to the perception that is itself based on feedback from the mechno-receptive machinery that is embedded in the body’s deformable tissues. Haptic perception is perception by means of the body, in concert with the general definition of perceptual systems [26,14]. It functions in two distinct ways, each of which may act either in isolation or concurrently: a) proprioceptively – perception of the body and perception of the body’s segments relative to the body as a unit and relative to each other, and; b) exteroceptively – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27]. The haptic system participates both – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27]. The haptic system participates both – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27]. The haptic system participates both – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27]. The haptic system participates both – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27]. The haptic system participates both – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27]. The haptic system participates both – perception of attachments to the body (e.g. handheld objects) and of surfaces adjacent to the body [27].

A Screw system with one dof control

In order to illustrate a screw system with a perception-action control scenario, a tridagnostic reconstruction of the diffusion tensor data derived from the muscle fiber tracking of the gastrocnemius lateralis muscle was performed (Diffusion Toolkit and TrackVis,
Department of Radiology, Massachusetts General Hospital, USA. The visualized action manifold contains muscle fibers characterized through approximately 600 tracks (Figure 1). The mean length (± standard deviation) of the tracks (representing the individual fibers) was measured as 66.9 ± 13.66 mm. The image of the gastrocnemius lateralis presented here originally had 3,474 tracks before filtering in order to facilitate the observation of the fiber directions.

For a screw \( p \) to belong to a screw system of the fifth order (5 DOFs), the necessary and sufficient condition is that \( p \) be reciprocal to one given screw \( q \) (Figure 1). This condition is expressed in the form:

\[
R(p, q) = (h + h')\cos\theta - \sin\theta = 0
\]

(1)

where \( h \) and \( h' \) are pitches of screw \( p \) and \( q \), respectively, is the angle between the two screw axes and \( a \) is the normal distance between the two axes. The expression defined by equation (1) is referred to as the virtual coefficient of a pair of screws and is of great importance in the present study because it provides an expression for the energy required to affect the displacement or muscle synergies used for equilibrium control during the stance phase (as stated earlier).

To define a one DOF control law of the simplest type, we started with the original notion of a multistage perception process. We now describe the importance of a policy of action. As indicated above, the value of \( q \), are to be chosen at each stage in a policy which minimizes the function, \( R(p, q) \), called the optimal policy [32]. Thus the perception-action control posed in this work will hinge upon the determination of a set of optimal policies, such that:

\[
f(p) = \min(R(p, q) + \min f(T(p, q)))
\]

(2)

The reciprocal screw system of the fifth order (5 DOFs) shall constitute complex lines on which wrenches act upon the body. These are triply infinite, or \( ∞^3 \) lines, which satisfy one given condition, such that one solution to equation (1) exists between a screw and the reciprocal screw system, i.e., a manifold of constraint forces satisfying equation (1). It also follows that the reactions of the constraints by which the movements of the knee are confined to twist about a screw system of one DOF, can only be wrenches on the reciprocal screw system with an order of five (5 DOFs). The fact that each twist of the shank, and, \( p_1 \), result in a third screw, \( p_{IAK} \), the twist of the thigh, connected through the knee axis of the series. Since \( p_1 \) and \( p_2 \) are appropriated to two different elements of the mass-linkage, no kinematic significance can be attached to the composition of the two twists on \( p_1 \) and \( p_2 \). If, however, the two twists on \( p_1 \) and \( p_2 \), having the proper ratio of amplitudes, had been applied to a single rigid body, the displacement produced is one that could have been affected by a single twist about a single screw, \( IAK \), on the cylinders (\( p_1, p_2 \)). If this intermediate screw is given, the ratio of the amplitude of the twists on the given screw may be determined as:

As a further comparison, let us devise two ratios on this special configuration of a screw system of the first order of freedom (1 DOF):

\[
\text{(ratio)} = \frac{\text{sum of the absolute values of the actuator twist-amplitudes divided by the amplitude of the end-effector twist}}{\text{the foot}} = 0
\]

\[
\text{(ratio)} = \frac{\text{sum of the absolute values of the actuator wrench-intensities divided by the intensity of the end-effector wrench}}{\text{the foot}} = \infty
\]

Even though a loss of constraint about the IAK during knee motion, as indicated by (ratio), causes such static instability that a special configuration should be strictly avoided whenever the knee is being controlled during equilibrium, there are other conditions during locomotion where directional compliance is sought. In such a situation, a control mechanism of the IAK might create knee motion that replicates a special configuration at which the screw system that was applied transitorily is made to match the desired compliance [35].

**Ball-Disteli diagram**

The Arnold-Kennedy theorem of three axes [36] may be manifested when two screws, \( p_1 \) and \( p_2 \), result in a third screw, \( P_{IAK} \) on cylindroids. In this application, consider the two screws as, \( p_1 \), the twist of the shank, and, \( p_2 \), the twist of the thigh, connected through the knee axis of the series. Since \( p_1 \) and \( p_2 \) are appropriated to two different elements of the mass-linkage, no kinematic significance can be attached to the composition of the two twists on \( p_1 \) and \( p_2 \). If, however, the two twists on \( p_1 \) and \( p_2 \), having the proper ratio of amplitudes, had been applied to a single rigid body, the displacement produced is one that could have been affected by a single twist about a single screw, IAK, on the cylindroids (\( p_1, p_2 \)). If this intermediate screw is given, the ratio of the amplitude of the twists on the given screw may be determined as:
\[ dv_i \mathbf{p}_i + dv_j \mathbf{p}_j + dv_{IAK} \mathbf{p}_{IAK} = 0 \]  

where \( dv_i \mathbf{p}_i \) is the twist of the shank, \( dv_j \mathbf{p}_j \) is the twist of the thigh, and \( dv_{IAK} \mathbf{p}_{IAK} \) is the relative displacement of the thigh with respect to the shank. The IAK is then defined by a linear combination of the two screws, \( \mathbf{p}_i \) and \( \mathbf{p}_j \) [36]. We can call upon the Ball-Disteli diagram that encapsulates the relation between the velocities of a pair of screws as well as the position and pitch of their relative screw motion, by referring to Plücker’s conoid, also known as Ball’s cylinder [37,38].

In order to create the Ball-Disteli diagram, we start by taking two generally disposed screws, \( \mathbf{p}_i \) and \( \mathbf{p}_j \), and for convenience place the \( x \)-axis along their common perpendicular with the half distance \( k \). The origin of coordinate \( \mathbf{c} \) is halfway between the screws and the \( x \)-axis is equally inclined by the angle, \( \sigma \), to the screws (Figure 3). A screw for the IAK, that is linearly dependent on \( \mathbf{p}_i \) and \( \mathbf{p}_j \), can be expressed as such after normalization:

\[ \mathbf{p}_{IAK} = \lambda_\alpha \mathbf{p}_\alpha + \lambda_\beta \mathbf{p}_\beta \]

where the corresponding coordinates of two screws on the principal screw can now be written as:

\[ \mathbf{p}_\alpha = [1,0,0;\alpha,0,0] \]

\[ \mathbf{p}_\beta = [0,1,0;\alpha,0,0] \]

Because \( \mathbf{p}_\alpha \) and \( \mathbf{p}_\beta \) are centrally placed in the system and enjoy other special properties, these have been called the principal screws of the system [39]. Thereby, for a variable transmission ratio, \( \frac{\lambda_\alpha}{\lambda_\beta} \), all relative axes are located on Plücker’s conoid, which as revealed follows a cubic surface (Figure 3).

Perception-Action coupling manifold

The screw system is designed ingeniously so that any deviation from equilibrium automatically generates a correcting force that tends to restore the system to equilibrium. In the simplest case, this restoring force is directly proportional to the disturbing forces. Although this case may appear to be the simplest, from the perception-action control point of view, control by policy is still more desirable. The perception-action coupling manifold, which is generated in terms of dual information surfaces during the stance phase of gait, is based on natural phenomena rather than an intellectual construct. In other words, perception-action coupling is a purely geometric representation of the subject-ground interaction. The perception-action coupling manifold, which utilizes correlating alignments of the mechanisms that generate the behavior of IAK and GRF through sensory feedback, can be used to investigate how a subject perceives affordances for effective locomotion [14]. The Ball-Disteli diagram will shift in position as the IAK shifts position so as to occupy a series of consecutive graphical positions in the diagram.

We can also determine the joint reactions due to the GRF in the same manner. If two wrenches act upon the knee, then the condition of equilibrium is met when the two wrenches are compounded by the aid of a cylindroid. For this condition, the single wrench that replaces the two wrenches shall lie upon that one screw of the cylindroid which is reciprocal to the IAK. The component wrenches within the reciprocal system are neutralized by the reactions of the constraints (Figure 4), while the remainder must compound into a wrench on a screw belonging to the screw system, which defines the freedom of the knee. We also perceived that a given wrench, GRF, \( \phi \), may be always replaced by a wrench of appropriate intensity on any other screw of muscles, in so far as the effect on a body only free to twist about is concerned. As such, we obtain:

\[ \eta \phi \delta_{\phi} + \phi \delta_{\phi} = 0. \]

Further, a wrench, can be always be expressed by a constraint force, at any point that resides on the IAK and a couple, in a plane through that point but not of course in general normal to the force (Figure 4). This statement should be clear since all the screws on the cylindroids are parallel to a plane. An analogy can also be made from
The above equation to the simple problem of the condition where two forces should be unable to disturb the equilibrium of a particle, only free to move along a straight line.

The algorithm for calculating reciprocal screws using the nullspace operation was previously developed [40] and later translated into computation functions (MATLAB, Mathworks, Inc., Natick, MA) [41]. The algorithm has also been used to describe the reciprocal connections of the IAK as associated with knee joint constraints. Our study here used the described framework to predict the constraint reactions within a reciprocally connected knee joint model.

To validate our modeling approach for the IAK during the stance phase of gait, we used previously published experimental data sets and compared their measured medial and lateral contact forces with our predicted ones. Data included motion capture kinematics (x-y-z trajectories of markers located at the patella, shank, and thigh), fluoroscopy information, ground reaction forces, electromyographical data, medial and lateral knee contact forces, and strength data [42]. An available knee radiograph contained a view of the joint in the frontal plane and provided geometrical information regarding the constraint force vectors. Published data were collected from an instrumented right knee replacement implanted in an adult male subject (subject code JW, mass 65 kg, height 1.7 m). The gait trial for the subject demonstrated a medial-lateral trunk sway gait pattern similar to that reported previously [43].

Results

The dynamic position of the IAK (Figure 3) was determined by the linear combination of two ISAs of the shank and thigh (equation 4 in Section 2). If, however, the two twists, \( p_1 \) and \( p_2 \), having the proper ratio of amplitudes, had been applied to a single rigid body, then the displacement produced could have been replaced by a single twist about a single screw IAK on the cylindroids \( (p_1 P, p_2 P) \). In the model presented in this paper, the one DOF equilibrium condition was considered such that the modeled knee was only free to twist about the IAK. A given GRF was replaced by a wrench of appropriate intensity on any muscle and both were compounded into a wrench, which is reciprocal to the IAK and resolved into component wrenches representing the lateral (Figure 5) and medial (Figure 6) contact forces belonging to the reciprocal screw system.

The measured instrumented knee data for the trunk-sway gait trials for the data sets were compared to the model prediction. The predicted maximum lateral and medial contact forces were 595.0 N and 1,092.0 N, respectively (Figures 4 and 5). The root mean square (RMS) errors during the contact of the foot with the ground were determined to be 148.1 N and 147.3 N for the lateral and medial forces, respectively (based on the stance phase shown in figures 5 and 6).

Discussion

The purpose of this study was to present a general theory as a perception-action control algorithm characterizing knee joint motion. We proposed the perception-action coupling manifold as a mathematical means to connect the instantaneous screw of the knee with the ground reaction force as a modeling approach that was verified by defined tasks in an estimation of constraint reactions. The coupling manifold can be directly implemented in the mathematical sense of a ‘minimum information framework’. We have demonstrated that a perception-action coupling manifold, generated in terms of two screw axes surfaces during the stance phase, can explain the interaction between gait kinematics and external applied forces. Therefore, the shape of the reciprocal condition in the perception-action coupling manifold can be regarded as a ‘minimal unit of analysis’ of gait pattern under all load-bearing physiological conditions. As reported here, there exists a unique one-to-one correspondence between the GRF and the IAK. The unique characteristic of the GRF-IAK relationship provides a new perspective on this topic of investigation. This approach may provide a metric toward assessing clinical implications addressing gait disorders on an individual patient-specific basis.

We have demonstrated that locomotion is controlled by affordances perceived by the exemplar subject. Specifically, a given GRF wrench on the surface can be replaced by a muscle wrench of appropriate intensity with any other screw. Hence, a one degree of freedom constraint during locomotion was not inhibited by disturbances during the support phase within the environment, i.e., the stance phase. It also follows that the reactions of the constraints, by which the movements of a knee are confined to twist about the screws of a system IAK, can only be wrenches on the reciprocal screw system of the fifth order (5 DOFs). As such, the reactions of the constraints are only manifested by the success with which they resist the efforts of certain wrenches, i.e., the GRF, to disturb the equilibrium of the knee. We replaced these contact forces by a perception-action coupling manifold as operationalized parameters. We introduced the basic conceptual move to create and control manifolds out of carefully chosen (theoretically motivated) state variables [44].

In conclusion, the presented approach can measure ‘dynamic alignment’ of in vivo knee loads. One can align the IAK with the GRF to reduce the payload on the medial/lateral compartment, thus instead transmitting the reaction (braking) torque to the knee. 

Figure 5: Comparison between the lateral force results of our theoretical approach and data gathered from an instrumented knee during trunk-sway gait trials (Fregly et al.) [42]. Differences between the predicted and measured values indicated an RMS error of 148.1 N.

Figure 6: Comparison between the medial force results of the theoretical approach and data gathered from an instrumented knee (Fregly et al.) [42]. Again, differences between the predicted and measured values had an RMS error of 147.3 N.
structure of the whole body. The reciprocal configuration (Figure 4) aligns a GRF with a reciprocal screw such that the reaction (braking) torques and forces on the joint are eliminated. Special orthotic or orthopedic treatments, which are rich in reciprocal configuration potential, may be designed for the post-treatment outcome of gait-related disorders. The optimal treatment incorporating the presented perspective requires further investigation. Overall, the essential geometric character of the described method seems particularly well adapted to provide an ecological solution for individual variability. Thus the mathematical framework articulates a sound foundation toward making gait analysis more diagnostically accurate.

Human biology is a field where complexities are raised in even the simplest models. The approach described here addresses the interface between psychology and physiology. In order to mathematically analyze physiologic control processes, we have introduced the basic concept of proprioceptively ‘information’, a term that does not refer to the highly specialized theory of coding [45]. In this application, we are thinking in a broader and more meaningful sense whereas our approach is based on the perception of affordances, i.e., possibilities for actions [14]. We have presented an approach, which has been neglected in contemporary modeling, toward examining the characteristics and accuracy of the environmental information available to the ambulating decision maker.

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