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Novel computational approaches characterizing knee physiotherapy

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Abstract

A knee joint's longevity depends on the proper integration of structural components in an axial alignment. If just one of the components is abnormally off-axis, the biomechanical system fails, resulting in arthritis. The complexity of various failures in the knee joint has led orthopedic surgeons to select total knee replacement as a primary treatment. In many cases, this means sacrificing much of an otherwise normal joint. Here, we review novel computational approaches to describe knee physiotherapy by introducing a new dimension of foot loading to the knee axis alignment producing an improved functional status of the patient. New physiotherapeutic applications are then possible by aligning foot loading with the functional axis of the knee joint during the treatment of patients with osteoarthritis.

Keywords: Instantaneous axes of the knee (IAK); Cylindroidal coordinates; Perception-action coupling manifold; Gibson's theory of affordance; Ball's screw theory; Joachimsthal's equation

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1. Introduction

A knee joint's longevity depends on the proper integration of five biomechanical variables: surface congruency, load distribution, stress during loading, contact area, and ligament tension. If some of the functional variables in a specific location are abnormal, the biomechanical system fails, resulting in arthritis. Knee osteotomy is an orthopedic surgical approach to realign the lower limbs by opening or cutting a bone wedge from the femur or tibia. This may be a better alternative than other types of knee replacement surgeries, especially for young people. However, knee osteotomy requires an understanding of the imbalance of stresses at the knee, defining an abnormal gait cycle, and cutting the bone wedge properly. This is a difficult procedure and can cause further damage and/or functional compromise. Indeed, knee osteotomy alone may not generalize most actions of the weight-bearing leg as accomplished by the adaptive movements of all the lower limb joints to the interactive surface.

While some computer-based surgical simulation systems have been developed to help surgeons perform knee surgeries [1], the knee models used are either not patient-specific [2] or lack kinematic and kinetic information [3, 4]. For example, subject-specific simulated [5] knee joint models were created from computed tomography (CT) scans while the subject-specific knee joint kinematics were obtained from fluoroscopic images. The modeling then predicted the medial and lateral tibiofemoral contact forces for different walking trials using static equilibrium in the tibial frontal plane [6].

No efficient method exists for patient-specific knee-model reconstruction [2], contact force computation, or visualization [7]. Furthermore, no system integrates contact-force simulation, gait-cycle simulation, and virtual knee physiotherapy. The use of mathematical models accepted in physiological research is much different from those applied to engineered mechanisms. Constraints are generally realized by rigid links and joints within actual machinery. However, most physiologic joints involve sliding, thus the center of rotation is defined instantaneously.

It is clear that human locomotion may be studied from a number of different points of view, e.g., anatomical, biological, mechanical, etc. 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/heal is in contact with a reaction surface. A classical theory of control-based approaches uses the optimization algorithm to fine-tune the muscle excitation patterns for each muscle group and produced a well-coordinated walking pattern that emulated the experimental data [8-10]. However, in order to reduce the number of degrees of freedom (DOFs) upon which the nervous system must operate, we have adopted the proposition that the interaction from the individual and the environment regulates movement though muscle synergies, or groups of

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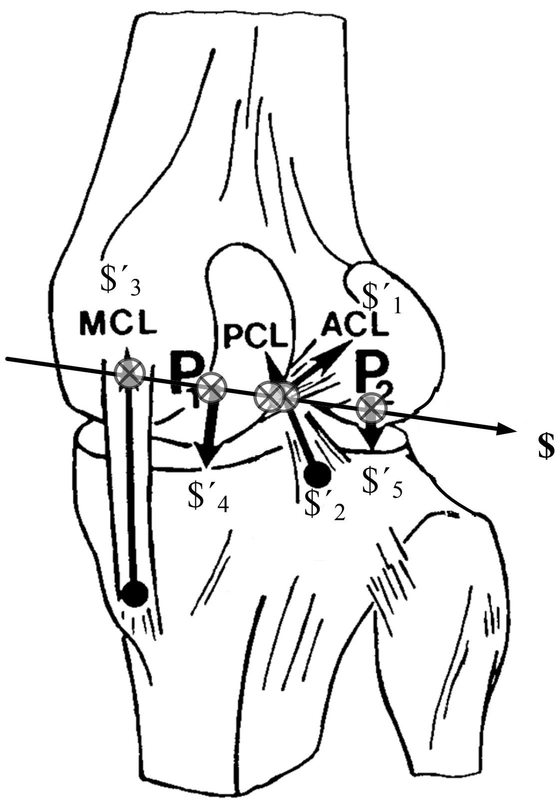

Figure 1. Five constraints \$'s are collectively reciprocal to the instantaneous screw axis \$. The instantaneous motion of the knee is guided by the constraints of the anterior cruciate ligaments (ACL), posterior cruiciate ligament (PCL), medial collateral ligament (MCL), and articular contact in the medial (P_1) and lateral (P_2) compartments. Note that no combination of the constraint forces that might be generated at the \$ will result in a rotation at the \$, and no angular velocity about the \$ will cause the constraint force to do any work at the points on the medial and lateral contacts. (Adapted from the original figure published in Kim and Kohles [24].)

co-activated muscles, rather than the nervous system controlling individual muscles [11, 12].

In this review, we propose an information based control theory whereby human locomotion is neither triggered nor commanded, but controlled [27, 49]. The basis for this control is the information derived from perceiving oneself in the world [13-16]. Central to this information-based approach will be the observed experimental sensory data [17]. Under the information-based movement control strategies [16], 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 associated with the performer [18]. A recent study confirmed that leg stiffness is not directly related to running mechanics, but rather, to the running environment [19]. The performer and his/her environment (the interaction surface) may be said to be co-participants in any resulting action. In this way, actions are specific to function rather than to mechanism [20].

The way that functional movement of a joint is constrained is related both to the location and the direction of its kinetic and kinematic axes. In other words, the kinematic constraints of joints are vector dependent. This in turn implies that constraints may be expressed in terms of linear- rather than point- based geometry as described in screw theory [21, 22]. Screw theory is based on the close relationship between line geometry and spatial kinematics [23]. It has previously been used to characterize knee function [24], explore the effectiveness of a golf club swing [25, 26], and as a method for minimizing interference from motion data. Essentially, symmetry exists between the extent to which a rigid body is constrained and its relative freedom of movement at each instant that a twist is produced.

The aim of this study is to review the foundation of novel computational frameworks for knee physiotherapies that involve the new concept of a perception-action coupling manifold connecting knee kinematics to the ground reaction vector in the sense of a 'reciprocal connection'. Muscle contraction and GRF are compounded into a wrench, which is reciprocal to the instantaneous axes of the knee (IAK) and resolved into component wrenches belonging to the reciprocal screw system. We established a framework for the estimation of reaction of constraints about the knee, in vivo medial and lateral contact force, using a process that is simplified by the judicious generation of IAK for the first order of freedom in equilibrium.

Herein, we discuss how we use data from gait analysis, information-based motion control algorithms, and interactive visualization to assist in knee physiotherapy. Our patient-specific knee informational framework helps us calculate the contact forces at the knee joint and in-turn perform virtual physiotherapy.

2. Materials and methods

2.1 Constructing a patient-specific knee model

Movements and postures are controlled and coordinated to realize functionally specific acts that are themselves based on the perception of affordances, i.e., possibilities for actions [18]. Therefore, during locomotion, we first investigate the complementary nature between the perception of the surface in terms of the ground reaction force (GRF) and the action of the individual in terms of the functional knee joint axes, as perception and action are inseparable [27, 28]. We have previously enunciated a principle which applies to the reciprocal screw system, which involves the theory of equilibrium with a freedom of the first order [15, 29].

It has been shown previously [24] that the forces which constrain the movement of the knee joint through an infinitesimal displacement are interlinked in terms of reciprocal