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Review Article

Observations on the Knee Functional Axis During Active Movements

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Abstract

Estimating the Knee Functional Axis (KFA) is crucial to both correctly implanting the prosthesis and accessing the joint kinematics. Researchers have mainly reported KFA by manual management of flexion-extension movements, which are passively performed without any voluntary movements. Active touch and movement refers to what is ordinarily called as touching, which is defined as variations in skin stimulation caused by variations in a person's motor activity.

The difference is very important for the individual. However, it has not been emphasized in the biomechanical literatures. This study aims to confirm the distinction between touching and being touched. We are particularly interested in measuring the Instantaneous Axes of the Knee (IAK) during locomotion. This geometrical "pattern" of the IAK is altered along with the touch pattern by the mechanical necessities of terrestrial movement.

Introduction

The correct estimation of patient-specific joint axis of the knee is crucial in achieving a reliable assessment of the musculoskeletal kinematics and dynamics [1]. Computer-Assisted Surgery (CAS) allows, for instance, to virtually define the patient-specific anatomy, which is mandatory to both correctly implant the grafts and assess the knee joint kinematics [2,3]. After lesion and ligament reconstruction, sensory and motor behavior changes are still observed because of the lack of proprioceptive information resulting from the reconstructed knee joint [4].

Nevertheless, despite its importance, the study of the human knee joint model, or the so-called "Knee Functional Axis (KFA)," has been largely confined to the investigation of passive movement with passive stimulation [5]. This aspect is treated simply as a part of the flexion-extension movements. The methods by which the KFA is estimated to date have been primarily passive, with either foot being in the neutral position or resting on a table. The limitation of these studies is mainly related to the manual management of flexion-extension movements, which are passively performed without control on voluntary muscle contraction.

Although the pattern may be elaborate, passive touch for the types and subtypes of anatomical receptors evidently involves three anatomically different receptive systems: in the joints, in the skin, and in the underlying tissue. However, active movement involves the concomitant excitation of receptors in the joints and tendons along with the new changing pattern in the skin, referred to as the "active touch." When a person touches surfaces with his foot, he produces the stimulation as it were. More exactly, the stimulation variations in the plantar side of the foot are caused by the variations in the person's motor activity. The difference is very important for the individual. However, it has not been emphasized in biomechanics, and particularly not in locating the KFA.

As regards the relation of touch to kinesthesis, psychologists seem to have assumed that active touch is simply a blend of two modes of sensations, kinesthesis, and touch proper. It is not often realized, even by anatomists, that it is the function of a joint not merely to permit the mobility of the articulated bones, but also to register the relative bone position and movement [6]. The organs of the knee fall into the perceptual system.

In contrast with the established ideas of what constitutes a sense, the senses considered as separate anatomical units have been treated as one perceptual system [7]. This is considered as a covariant haptic system. Therefore, joints yield geometrical information. The skin yields contact information, and they yield information specifying the layout of external surfaces in a certain invariant combination. Gibson has recognized that some of the stimulations produced by responses yield objective as well as subjective information [8,9]. As will later be suggested, the flow of stimulation in active movement contains two components, one *extrospecific* and one *propriospecific*. The capacity to attach something to the body suggests that the boundary between the animal and the environment is not fixed at the skin surface but can shift. The absolute *duality* of "objective" and "subjective" is more generally suggested to be false [10].

Attempts to characterize "the stationary configuration of the knee" of the knee joint have recently been conducted by measuring the Instantaneous Axes of the Knee (IAK), yielding information about joint position as well as Ground Reaction Forces (GRF), yielding active touch of the foot [11]. The use of this reciprocal system introduces a new dimension of foot loading to the knee axis alignment (i.e., the relation of touch to kinesthesis). This insight shows that locating the knee functional axes is equivalent to the static alignment measurement.

The IAK [11-13] is proposed to play an integral role in understanding the equilibrium function in postural maintenance occurring in response to gravity and ground reaction and in postural stabilization occurring in response to a perturbation [14].

This paper describes the biomechanical method relating foot touch to knee joint movement to determine the IAK compulsory to the patient-specific joint axis of the knee. The hypothesis being considered here is as follows: the IAK is the result of the perceptual action because it adjusts perceptual information obtained from the environment as contrasted with the merely passively imposed knee axis. This study is not heavy on theorems, and we start from scratch. In fact, the aspects presented in the background are well established. With a few exceptions, we anticipate that the avid reader would supplement the contents with available literature, some of which is historic but readily available.

Figure 1: Original system of knee complexes in involution: Five constraints $'s are collectively reciprocal to the instantaneous screw $, indicated as $\otimes$. That the virtual coefficient should vanish is the necessary and the sufficient conditions [13], or the pair ($ and $') are in involution,

$$\Omega_{\$\$'} = (h + h')\cos\theta + a\sin\theta = O$$

In the language of Plücker a system of lines in involution forms a *linear complex* as defined in Figure 2. Note that a system of lines thus defined belongs to a screw *five-system*, when six lines, $\$_1...\$_6$, are so situated that forces acting along them equilibrate when applied to the knee joint, which is free to twist about the IAK. We speak of the six lines so related as being *in involution*. (The figure was originally published by [22]).

Method

Types and subtypes of knee receptors involved in active movement

Active movement involves the concomitant operation of anatomical components, in which a foot touching the ground and the rotation of the joints are combined with the voluntary muscle contractions. The total stimulation flux involved in the so-called active movement is enormously complex. However, lawful modes of combination occur. We presume that the modes of combination of these inputs specify the difference between touching (active) and being touched (passive).

As regards the stimulation flow on micro-scale modality (i.e., "mechanotransduction") [15], the inverse dynamics problem developed for structural dynamics translates measurements of local state variables (at the cell level) into an unknown or desired forcing function at the tissue or the ECM level. A representative comparison between cell to tissue (inverse) and tissue to cell (boundary value) modeling illustrates the multiscale applicability of the inverse model [16]. The resulting external mechanical conditions can be judged "unique" by comparison with known in vivo human joint and tissue loads as shown here from normal (i.e., healthy) function [17].
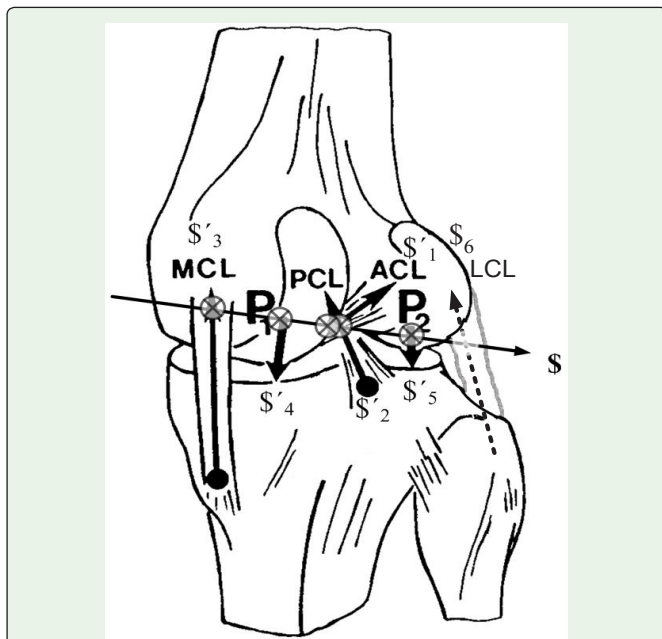
We chose in a sense to take a classical approach here toward establishing a model of duality for meaningfully combining the knee axis and foot touch. Joints in multibody systems are modeled by their joint axis as a screw $, which is a geometrical element on its own right, to relate touch to kinesthesis (Figure 2). The screw is a "line with an associated pitch" [18]. Jessop and Ball [19,20] recognized the relation of touch to kinesthesis and the duality between the static and the kinematic. Therefore, the screw has been poised for more than 100 years to unify the sciences of kinematics and statics.

Classifying quantities in terms of power is always meaningful in human movement. Power is used to decompose kinesthesis and touch into meaningful information onto the subspace. For example, reaction forces are wrenches $' that provide zero power (Figure 1), and that application axes pass through the instantaneous axes of the knee (IAK), $. The joint space is the subspace of the relative motion between the two bodies, which the joint connects [21]. The subspaces are being defined according to their power relation. The joint axis $ also defines the reaction subspace R composed of all $' as its null-space through the following equation:

$$\$^T R = 0 \qquad (1)$$

This equation provides one meaningful subspace $ for the IAK and one $' for the reaction forces, whose relation is termed as "reciprocal" [22].
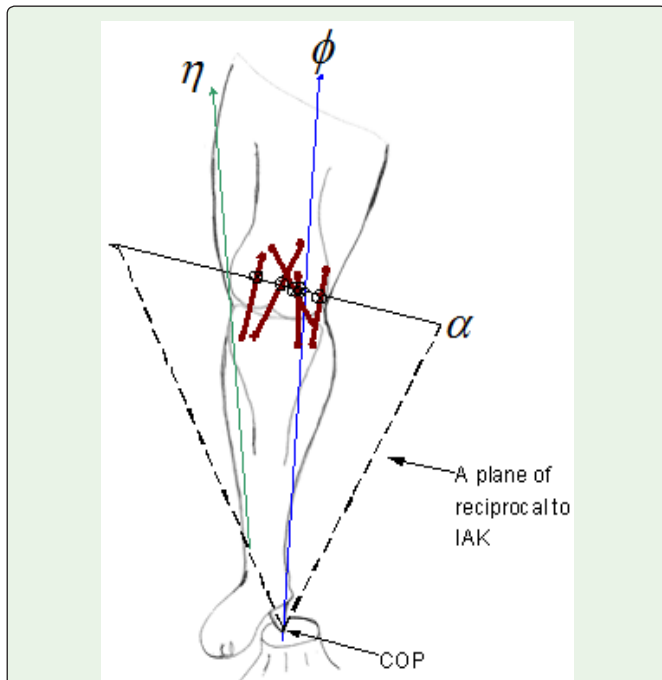
The knee perceptual system includes muscles, Anterior Cruciate Ligaments (ACL), Posterior Cruciate Ligament (PCL), Medial Collateral Ligament (MCL), and articular contact in the medial (P_1) and lateral (P_2) compartments (Figure 1). We have shown that six constraints are members of the "Joint Reaction Subspace (JRS)" and are so situated that forces acting along them equilibrate when applied to a knee joint, a certain determinant vanishes, and the six lines (i.e., "*knee complex*") are *in involution*, which are collectively reciprocal to the IAK [22]. Each of the six lines is the linear combination of the other five lines. The theorem is attributed to Möbius, who has shown

Figure 2: The knee joint provides the instantaneous screw α which is reciprocal to the impulsive ground reaction force ϕ. No combination of angular velocity about the α axis will cause instantaneous translational movement, while any force at the ground contact will not cause a rotation about α. The reaction forces (and torques) of the GRF will then be taken up by the musculoskeletal structures with the limb. Muscle contraction η and GRF ϕ are compounded into a wrench, which is limited to a plane of COP and reciprocal to the IAK. The reciprocal forces reside in the plane is resolved into component wrenches belonging to the reciprocal screw system of the five components as indicated in the Figure 1. 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. Adapted from the original figure published in [13].
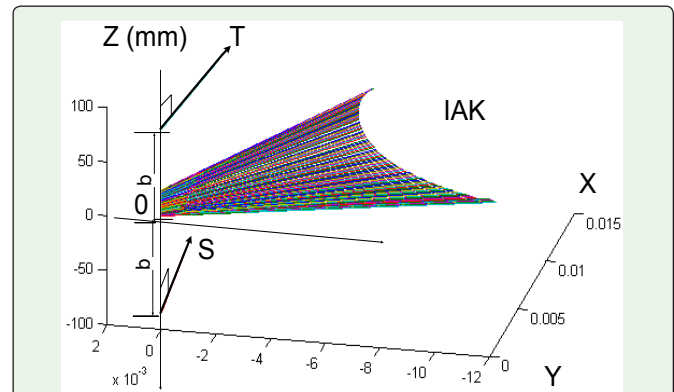
Figure 3: In order to create the cylindroids diagram, we start by taking two generally disposed screws, **P₁** and **P₂**, and for convenience place the z-axis along their common perpendicular with the half distance *b*. The origin of coordinate **O** is halfway between the screws and the x-axis is equally inclined by the angle, σ to the screws. A screw for the IAK that is linearly dependent on **P₁** and **P₂**, can be expressed as such after normalization: The cylindroids diagram itself aligns itself using the principle of three axes.

Mode of stimulation-information: knee complex in involution

Active touch is composed of a certain special combination of inputs in the joint-and-tendon receptors. It probably carries information about the object being touched. An organ of the body is being adjusted for registering information [7,8]. The limbs and extremities are motor organs as well as sensing organs. However, the motor performance function can be subordinated to the exploratory adjustment function in the case of the limbs. The single term, "kinesthesis," cannot carry the burden of all meanings that have been added to its original meaning. Hence, we try to emphasize herein the multiplicity of the so-called kinesthesis by utilizing different combinations of these inputs and to different functions of these combinations.

Shank *S* and Thigh *T* are appropriated to two different elements of the mass linkage (Figure 3). Therefore, no kinematic significance can be attached to the composition of the two twists on *S* and *T*. Note that nothing has been asserted about the performatory movement of the knee as when an object is relocated or a tool is wielded. Hence, we only consider a perceptive small movement (i.e., a twist on a screw). However, the displacement produced is one that could have been affected by a single twist about a single screw (i.e., IAK) on the cylindroids (*S*, *T*) if the two twists on *S* and *T* with the proper ratio of amplitudes had been applied to a single rigid body. We have shown that the IAK is defined by a linear combination of the two screws belonging to the cylindroids.

Presumably, the modes of combination of these two inputs (*S*, *T*) specify the differences between touching and being touched. An individual reaction force that produces no power in the JRS has an application axis that passes through the IAK, $. Equivalently, the resulting reaction forces in the ligaments lie on the application axis of $′ (Figure 1). Accordingly, the line of force $′ residing between the two inputs (*S*, *T*) must be incapable of causing a change in the relative displacement $ that exists between these two bodies. In other words, the desired (I/O) relationship cannot be achieved if the line of force $′ is not reciprocal to $.

that forces about six lines can equilibrate and the sixth line is limited to a polar plane if five of the lines and a point on the sixth line be given. Ball classified the *knee complex in involution* as a five-system that proceeds via their reciprocal one degree-of-freedom system [20].

We found that the GRF vector is limited to a plane in the knee complex of one degree-of-freedom [23] if the IAK is given and a location of the Center of Pressure (COP) on the axis of the Ground Reaction Force (GRF) is known (Figure 2). This aligns the knee joint with the GRF such that the reaction torques are eliminated. The reaction to the GRF will then be carried by the musculoskeletal structure of the leg, and not by the knee itself, thereby representing the stationary knee configuration [11].
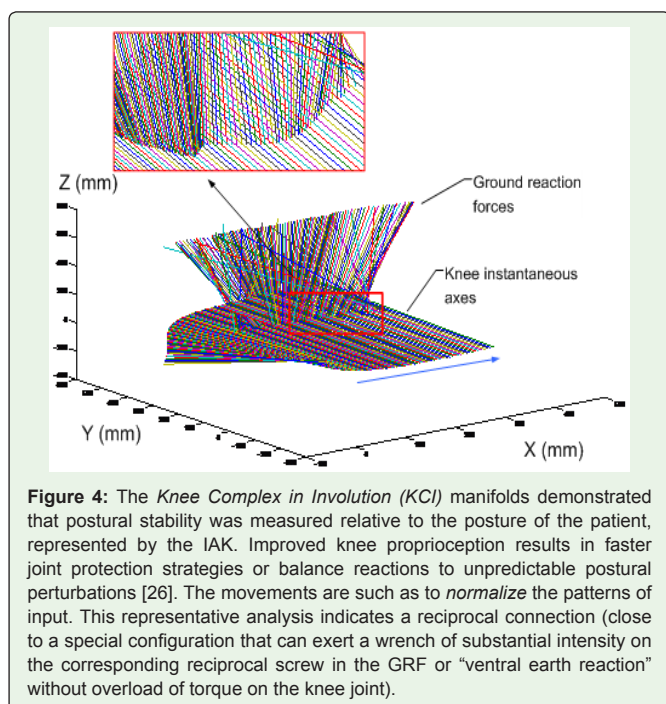
The knee joint can be considered to be in a state of reciprocal configuration when the IAK is reciprocally connected to the GRF during the stance phase of movement. A considerable GRF can be exerted during the stance phase of the leg within the gait cycle when the axis of the said GRF nearly coincides with a reciprocal screw. This stationary configuration within the stance phase is important because the knee can then exert a wrench of substantial intensity on the corresponding GRF vector (Figure 2), without engendering an overload of JRS [11].

An infinite of wrenches (loads) or candidate contact normals $' are reciprocal to the single screw or JRS defined by the IAK. The subspace is defined with meaningful information, such that the involution (1) induces an involution on each line common to the JRS. In other words, the reaction forces within the two inputs (S, T) lie on a common line of both the JRS. We can term this actual experience as the *Knee Complex in Involution* (KCI). The knee system under the condition of KCI performs similar to a single rigid body structure with one degree-of-freedom, thereby achieving both a twist about one definite screw IAK and the desired relationship of touch to kinesthesis.

Results

We measured the KCI through readily accessible benchmark data [24]. Noticing the fluctuation of the intensities of cutaneous sensation becomes difficult when the variations in the touch pattern in terms of its intensities, as well as directions, are covariant along with the variations of the movement pattern in terms of IAK. The observer is primarily aware of the substance and its resistance of the surface (Figure 4). As regards the issues of relating the reciprocal connection [22] (zoomed up pan in Figure 4) between impulsive touches, GRF, and covariant postures, IAK enunciates that the perceptual system registers the covariance of cutaneous and articular movement information.

The upward pressure of the surface of support on the ventral side of the foot provides a constant background of stimulation for every terrestrial animal. It is covariant with the continuous input of the appropriate receptors of the articular movement in the knee joint already mentioned. Together, they provide what the ordinary person calls the "sense of support." The axis of gravity and the plane of the ground provide the basic frame of reference for tactual space perception. As will appear, active touch yields clear perceptions of the environmental space in the absence of vision.

Figure 4: The *Knee Complex in Involution (KCI)* manifolds demonstrated that postural stability was measured relative to the posture of the patient, represented by the IAK. Improved knee proprioception results in faster joint protection strategies or balance reactions to unpredictable postural perturbations [26]. The movements are such as to *normalize* the patterns of input. This representative analysis indicates a reciprocal connection (close to a special configuration that can exert a wrench of substantial intensity on the corresponding reciprocal screw in the GRF or "ventral earth reaction" without overload of torque on the knee joint).

Therefore, a one-to-one correspondence exists between the impulsive reaction forces and the instantaneous screw axis. To express this differently, the complexes of instantaneous and impulsive screws are projective, powerless forces passing through the IAK and merging into KCI. We also perceive that a given wrench (i.e., GRF) may be always replaced by a wrench of appropriate intensity on any other screw, in so far as the effect on the knee only free to twist about the IAK is concerned. The IAK screws are shown to nearly coincide with a reciprocal screw of the GRF as indicated in the zoomed image.

Figure 4 presents a measure of KCI for a species of observer, which has been measured relative to the observer (i.e., relative to the posture and behavior of the observer being considered). The touch and vector patterns are altered together by the mechanical necessities of the terrestrial movement. The covariance of cutaneous and articular movement is information in its own right.

Discussion

A series of observations, both introspective and behavioral, confirms the distinction between touching and being touched. The former is a channel for a great variety of information about the environment. However, whether it should be considered as one or several senses is a matter of definition. The simple formula consisting of passive touch plus kinesthesis is insufficient. The hypothesis of two components of stimulation, namely, extrospecific and propriospecific, is more promising. The covariance of cutaneous and articular motion is information in its own right.

Biomechanical experiments have generally not realized that applying stimulation to an observer is not the same as for an observer to obtain a stimulus. Obtainable stimuli can be controlled and systematically varied, just as applied stimuli can be. Psychophysical experiments are possible for tactual perception as well as for cutaneous sensitivity if appropriate methods are devised to control the obtainable stimuli. The change in the stimulation pattern by altering interventions could be predicted as a single visualization, such as in Figure 4. Therefore, altering the walking mechanics and muscle coordination patterns through interventions directly influences the KCI conditions, which results in altered joint forces. We need to establish a new paradigm for braces and orthoses intended to reduce load that promises a beneficial effect. Is the aspect of unloading essential? Are stability and proprioception the most important factors? The latter questions can be answered by exploring the optimally tuned knee satisfying the KCI condition.

Hence, the stimuli with one excitatory capacity for a receptive subsystem in passive touch will have a different excitatory capacity in active touch, which is a different specificity. The relations between the subsystem stimulations become significant. A lawful combination of the inputs carries information different from that carried by isolation of the inputs and yields a different perception. Lumping one set of receptive systems together as touch and another as kinesthesis then obscures the function of the systems in combination. Anatomically different receptors may serve the same function and arouse the same experience. Moreover, they may serve different functions in different combinations. Henceforth, dropping the term "individual anatomical unit" and speaking instead of "knee complex in involution" might be better.

We have long waited to acknowledge that the normal everyday knee axis is a truly obtained stimulus and not an imposed one as we

have so long assumed. The remarkable thing about this new concept of active proprioception of IAK, as contrasted with the old one of passive IAK, is that we can no longer consider the stimulation of the knee axis apart from the adjustment of accommodation, modulation, or stabilization that determine what the IAK will be. The IAK movements tend toward equilibrium of clarity, and not of need-reduction [25]. Equilibrium is a process of continuous compensation, where the input, and not the output, is optimized [7] along with this ongoing "tuning" of nervous centers that filters out irrelevances [25].

We have demonstrated that subtler activities of the perceptual organs are hidden in the gross motor response as presented in the KCI remaining in equilibrium by fixing on and clarifying the relevant stimuli. Therefore, we should choose surgical procedures that not only reconstruct the anatomy, but also restore functioning in the original knee complex in involution, where the line of force in any reconstructed graft must be incapable of causing a change in the IAK. In other words, KCI is the necessary and sufficient condition to consider when avoiding impingement.

In conclusion, by observing the locomotion performance, we propose an unrecognized mode of experience called the "knee complex in involution." This mode goes beyond the classical modalities of touch and kinesthesis. The approach demonstrates the alignment of the IAK associated with the GRF reducing the payload on the medial/lateral compartments, thereby transmitting the reaction (braking) torque to the structure of the limb, or termed as a performance model of the KCI.

The KCI could serve as units of the perceptual system, in which a given GRF may be always replaced by a force of appropriate intensity on any other subcomponent in so far as the effect on a knee only free to twist about the IAK is concerned. This alignment then eliminates the internal reaction (braking) torques and forces within the joint.

Acknowledgements

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