Chapter

The Knee Proprioception as Patient-Dependent Outcome Measures within Surgical and Non-Surgical Interventions

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Abstract

Proprioception considered as the obtaining of information about one's own action does not necessarily depend on proprioceptors. At the knee joint, perceptual systems are active sets of organs designed to reach equilibrium through synergies. Many surgical procedures, such as ACL reconstruction in personalized medicine, are often based on native anatomy, which may not accurately reflect the proprioception between native musculoskeletal tissues and biomechanical artifacts. Taking an affordance-based approach to this type of "design" brings valuable new insights to bear in advancing the area of "evidence-based medicine (EBM)." EBM has become incorporated into many health care disciplines, including occupational therapy, physiotherapy, nursing, dentistry, and complementary medicine, among many others. The design process can be viewed in terms of action possibilities provided by the (biological) environment. In anterior crucial ligament (ACL) reconstruction, the design goal is to avoid ligament impingement while optimizing the placement of the tibial tunnel. Although in the current rationale for tibial tunnel placement, roof impingement is minimized to avoid a *negative* affordance, we show that tibial tunnel placement can rather aim to constrain the target bounds with respect to a *positive* affordance. We describe the steps for identifying the measurable invariants in the knee proprioception system and provide a mathematical framework for the outcome measure within the knee.

Keywords: knee proprioception, knee-tensegrity-structure (KTS), affordance-based-design, ACL impingement, knee synergy, entrainment, instantaneous knee screw (IKS)

1. Introduction

1.1 Anterior crucial ligament reconstruction and tibial tunnel placement

The anterior cruciate ligament (ACL) is a critical knee joint, bone-to-bone connected, stability ligament that is attached from an anterior location of the proximal tibia to a posterior location of the distal femur. The ACL is highly susceptible to failure during athletic activities and slip-fall events. The goal of ACL reconstruction surgery is to rebuild the ligament attachments as closely as possible to the native anatomy in order to restore pre-injury knee function and normal proprioception in the affected knee [1]. Personalized medicine in surgery allows the customization of insertion sites, graft size, tunnel placement, and graft tension for each individual patient [2]. A critical pre-operative decision concerns the placement of a tibial-femoral tunnel mimicking the native orientation of the ACL attachment [2]. Surgeons need to consider particular aspects of the local anatomy and, by extension, the biomechanical artifacts introduced during surgery. Here, we report an alternative approach based on the understanding of knee affordances to guide surgeons in the design of knee reconstruction strategies.

As aforementioned, an important predictor of clinical outcome during ACL reconstruction is tunnel placement [3, 4]. Roof impingement occurs when an ACL graft prematurely contacts the intercondylar roof before the knee reaches terminal extension. A tibial tunnel anterior to the tibial intersection of the intercondylar roof's slope allows the distal half of the roof to impinge on the anterior surface of the graft (*arrow I* in **Figure 1(a)**). Impingement syndrome occurs when the relationship between two articular components are incongruous, with resulting friction, inflammation, and degeneration [6]. Failure of grafts placed anteriorly is likely due to the impact of the bony roof on the graft's anterior surface during knee extension (**Figure 1(b)**) [5].

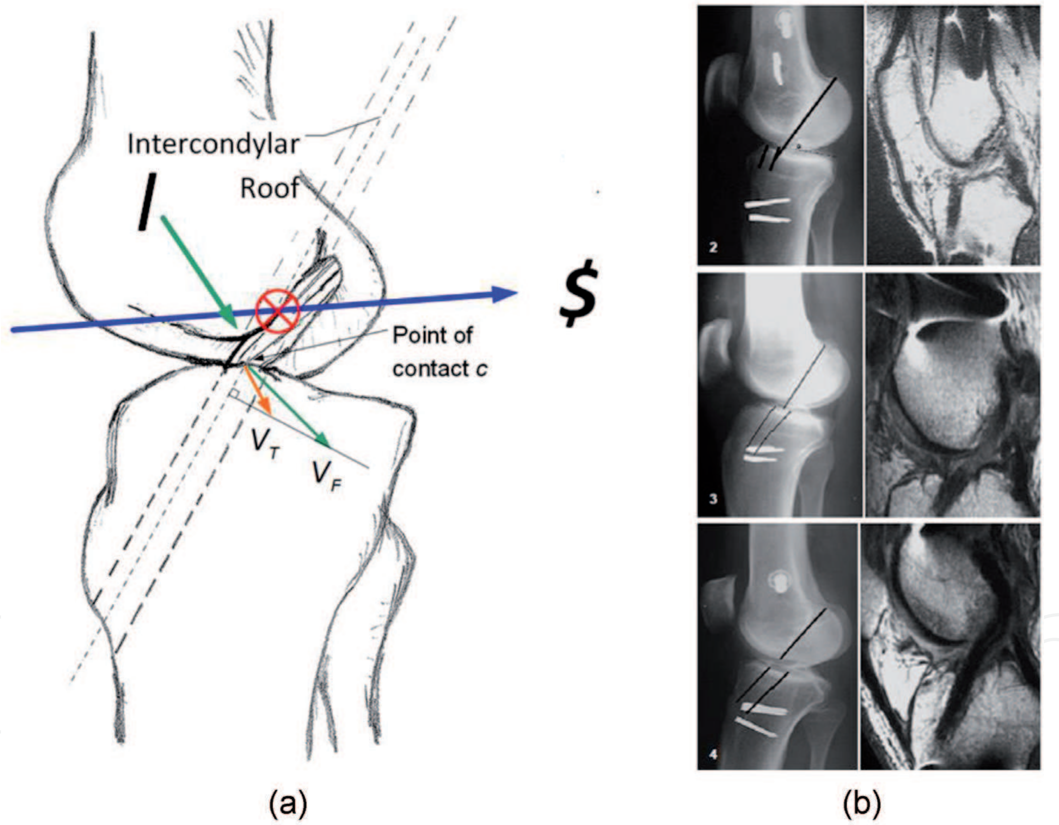

Figure 1.
(a) Schematic representation for the surgical placement of the tibial-femoral tunnel, presenting the possibility for uniform motion transmission within the knee. The (positive) affordance based *approach encourages surgical designers to customize the position of the tibial-femoral tunnel to intersect with the instantaneous knee screw (IKS or $). The point of contact (c) is determined from femoral and tibial velocity vectors during joint movement (V_F and V_T, respectively). (b) Radiographic and magnetic resonance images (MRI) of an exemplar of tibia tunnel placement leading to roof impingement during ACL reconstruction.* Negative affordances *(severe and moderate impingement) inform about the tunnel locations to avoid, in order to prevent roof impingement of the ACL. Severe roof impingement occurs when the surgeon places the tibial tunnel in a local totally anterior to the slope of the intercondylar roof (top). Moderate roof impingement occurs when the surgeon places the tibial tunnel in a local partially anterior to the slope of the intercondylar roof (middle). A graft may also become impinged when the surgeon places the tibial tunnel in a local entirely posterior and parallel to the slope of the intercondylar roof (bottom). An impinged graft has a low, uniform signal intensity on the MRIs. The original schematic and images were published previously [5] and are used by the permission of Dr. Stephen Howell.*

To our knowledge, this is the first study to use psychological theory to address this surgical design concept [7]. Traditional rating systems to assess clinical outcome after joint arthroplasty are often based on the surgeon's objective ratings, such as range of motion and strength, or clinical ratings of function and pain. However, the patient's perceptions after arthroplasty may differ significantly from those of their clinician. Moreover, surgeons often underappreciate the needs and views of their patients [8]. There is, therefore, increasing awareness of the need to include patient-reported outcome (PRO) instruments in the evaluation of surgical procedures. Indeed, these patient-centered assessments of treatment outcomes are becoming today's standard [9]. Patient-reported outcome metrics (PROMs) can be simply described as a patient's health status self-report. A 'forgotten joint score', corresponding to when a patient forgets the artifact in their everyday life, was introduced in PROM as the ultimate goal in joint reconstruction [10]. 'Forgotten joint scores' are often observed in patients after surgery [11]. Nevertheless, these ratings do not replace the need to understand the general role of artifacts and affordances in reconstruction surgery. This study aims to identify measurable invariants using a (positive) affordance-based design strategy for structural tunnel placement during ACL reconstruction.

2. Affordance-based design

Current approaches in design science are characterized by a strong emphasis on methods as opposed to theory. Herbert Simon [12] was one of the early proponents studying design as a science. In the 1960s, Simon criticized the lack of a theoretical basis in design methods, describing such ad hoc methods as 'cook-book approaches.' Novel conceptual frameworks for design allow engineers to better describe and solve problems at the system level, such as those involving user interactions. We propose a conceptual approach for design based on affordances, a concept used in the study of perception in ecological psychology.

'Architecture and design do not have a satisfactory theoretical basis,' wrote psychologist James J. Gibson three decades ago. He also asked, 'can an ecological approach to the psychology of perception and behavior provide it?' [13]. Gibson's affordances theory describes how animals perceive their environment [14]. We applied Gibson's concept of affordance to the design of artifacts, in particular anatomic artifacts, which impacts on their biomechanics.

A decade after Gibson's seminal work, another psychologist, Donald A. Norman, use Gibson's theory of affordance to understand artifact design [15]. However, Norman's approach stopped short of incorporating the concept of affordance as fundamental to the design of any artifact [16]. When Norman revised the 1988 edition of his book in 2013, he rejected the ecological theory. He noted that the term affordance was often misused by psychologists, and as a result, he introduced the term 'signifier.' Signifiers make explicit that affordances are inputs used during cognitive deliberation for creating internal mental representations, which contradicts Gibson's claims that, if a designer successfully makes affordances possible, the artifact directly informs how it can be used—which is the hallmark of successful design. Intriguingly, in a recent study [17], Norman regrets that different psychology fields and design science have become separate silos unable to communicate with one another.

Ecological psychologist William Warren has applied the concept of affordances to the design of specific artifact-user relationships, such as the height of stairway steps [18]. His approach relied on the ratio of leg height to step height. Paola Cesari followed up on Warren's stair climbing studies by showing that older people perceive stairs differently than young people. However, the ratio between step height and the distance between the stepping foot and the top edge of the step was similar in both groups [19].

Since the concept of 'affordance' was introduced almost 40 years ago, it has been used in a variety of fields, including child psychology [20], the design of graphical user interfaces [21], mobile robots [22], control room interfaces [23], and more recently, in engineering design [24–26]. The impetus for any design project can be understood in terms of creating and changing affordances. The design process is the construction of an artifact that offers specific affordances, but not certain undesired affordances. An artifact with more positive affordances is considered better, while an artifact with more negative affordances is considered worse. However, this approach does not follow ecological psychology, but instead, it addresses the difficulty of identifying affordances with engineering [27].

Maier and Fadel coined the term artifact-artifact affordance (AAA) [24, 25]; however, AAA has not been properly incorporated within the larger theory of affordances. Although AAA was developed as a new concept, the idea that inanimate objects offer action possibilities in an organism is a foundational concept known since Gibson's work in ecological psychology. The ecological approach demonstrates how animal (including human) perception and action is continuous with interactions between inanimate physical systems, or the world in general. The entrainment of separate limbs during biological coordination, for example, follows the same physical laws as entrainment between two pendulum clocks or other purely mechanical (inanimate) systems [28]. The fact that interactions between inanimate and animate systems are continuous precludes the need to identify AAA as a distinct category.

In short, these concepts should be used with great care if knowledge is to be gathered. In the present study, we used a surgical technique as an example of how the theory of affordances may be utilized for affordance-based design.

3. Artifact-user affordances versus artifact-artifact affordances

Gibson demonstrated how animal perception and action is continuous, with interactions with inanimate objects or surfaces [14]. The affordances of a product are what it provides, offers, or furnishes to a user. Gibson's 'system theory' of perception corresponds to an open system, which is rather different from the view of isolated artifacts [29]. For engineering design, an affordance can be defined as the relationship between person and artifact from which the behavior emerges. These affordances between artifacts and the people that use them are called artifact-user affordances (AUA).

For example, the gear pair (**Figure 2(a)**) is referred to as an artifact-artifact affordance (AAA) for uniform motion transmission between two parallel axes, and it is possible only if the line of action passes through a fixed point, known as the pitch point. Moreover, assuming that gear 1 rotates with constant angular velocity ω_1 , the motion is transferred by direct contact at points K1 and K2. The objective is to determine whether or not the angular velocity ω_2 will remain constant or present uniform motion transmission. Kennedy's theorem identifies the fundamental property of two interacting rigid bodies in motion [30], such that three instantaneous centers shared by three rigid bodies in relative motion to one another, all lie on the same straight line. Uniform motion transmission between two parallel axes is possible only if the line of action passes through an invariant point, known as the pitch point. The pitch point is the instantaneous center of velocity for the two gears. For the gear teeth to remain in contact, the two-component velocities along the common normal must be equal. The absolute velocities along the line of action must

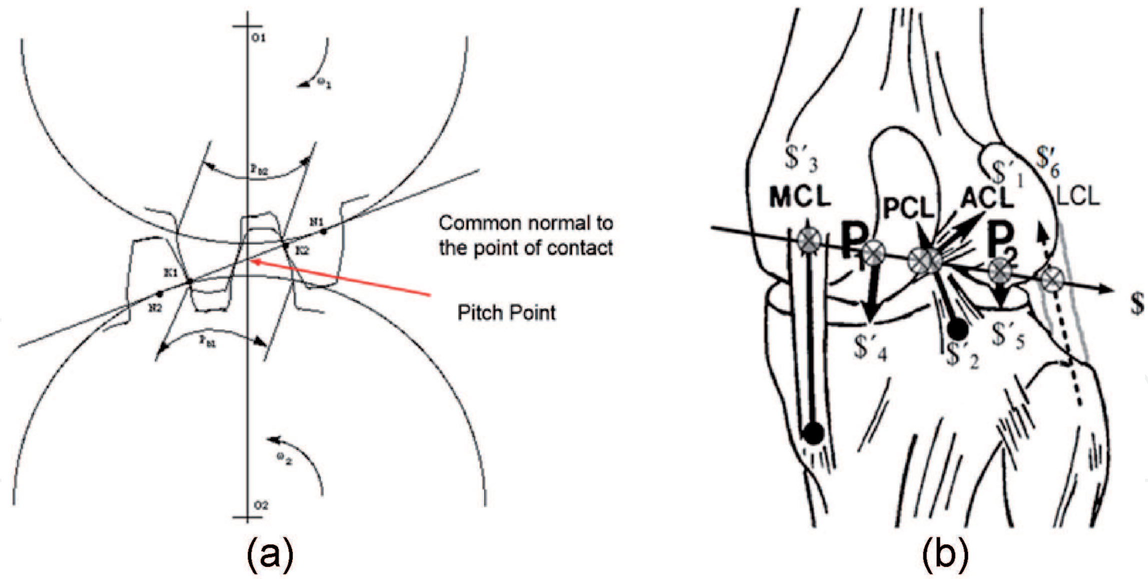

Figure 2.
(a) The artifact-artifact conjugate action, in the form of two interacting gears, demonstrating the uniform motion transmission between two parallel axes as can be found in a knee joint. (b) the knee joint synergy as represented by six constraints $\left(\$_i', i = 1,..,6\right)$*, which are conjointly reciprocal to the instantaneous knee screw ($) as indicated by their intersections (at the ⊗ 's). A balance of forces happens when the virtual coefficient vanishes, being it the necessary and sufficient condition for knee equilibrium.*

be identical; otherwise, bodies 1 and 2 become separated. It was shown that if the involute profile describes *the gear profile*, the common normal does not change its direction because it is an invariant of the structure. However, this may not be the case if we consider it in terms of affordances.

Gibson claims that some affordances are beneficial while others are injurious, such as maintaining a line of action versus veering off course [14]. These benefits and disadvantages, safeties and dangers, positive and negative affordances are properties of events taken with reference to an observer, and not properties of the observer's experiences; they are not personal values or feelings of pleasure or pain added to neutral perceptions [14]. For example, physical properties of the tibial tunnel and the intercondylar notch roof are not affordances in and of themselves, but they do determine what affordances are offered to a surgeon depending on a patient's anatomic features. Thus, the characteristics that affect positive AUA are the same as those affecting negative AUAs. The artifact only has one set of characteristics, which is a customization of the tunnel placement, and this is all that the designers or surgeons can act upon. As a consequence of such mutuality, affordances do not exist in the patient's tunnel or intercondylar roof, but in what they offer to the surgeon. Importantly, AUAs may conflict with one another when the graft becomes slack or loose (i.e., loss of extension in the graft at full extension, or the graft being trapped in the notch), indicating a negative affordance or an increase in the potential for injury. Thus, when a surgical designer identifies a functional range in which a joint is not allowed to fail, they need to constrain the target bounds for that same joint to enhance positive affordances and avoid negative affordances. This approach is addressed in the section below.

4. The affordance-based design applied to reconstructed knee joint function

A joint 'gear' cannot perceive itself or its joint gear since gears are inanimate. Gears simply conjugate uniform motion transmission by virtue of their tensegrity structure, manifesting that structure influences behavior [31]. However, the knee is an active set of bone structures that come to equilibrium via a joint function. The function of a joint is not only to permit mobility of the articulated bones but also to maintain a stable bone position and movement. Knee structures include muscles/tendons, anterior cruciate ligaments (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL), and articular cartilage contact in the medial (P_1) and lateral (P_2) compartments (**Figure 2(b)**). From a biomechanical point of view, several studies have shown that these intra-articular knee structures work in synergy with the ACL [32–34]. The knee synergy engages afferent/efferent motor control loops that establish functional equilibrium gait patterns [35].

Neurophysiologist Nikolai Bernstein defined coordination as mastering the many degrees of freedom (DOF) of a particular movement by reducing the number of variables to be controlled [36]. Recently, a contemporary perspective on Bernstein's concept of synergies has been proposed [37]. The muscle synergy is equivalent to the complexity of lines, a manifold approximated by individual fibers (**Figure 3(a)**). Muscles are not functional units, even though this is a common misconception. Instead, most muscular movements are generated by many individual motor units distributed over some portions of one muscle, plus portions of other muscles. The tensional forces of these motor units are then transmitted to a complex network of fascia sheets, bags, and strings, which convert them into the final joint/body movement [38].

Line manifold contraction is a linear line complex [39] defined by screws ($IS(\mathbf{p})$) (**Figure 3(b)**). Bodies twist around a screw, called Instantaneous Screw [40]. In any screw motion along a line axis forming a linear complex, the lines remain within the complex. Additional cognitive processes or internal representations are not needed to explain these phenomena, as perception and action are coupled. Perceptual systems are active sets of organs designed to reach equilibrium through synergies [41]. A body

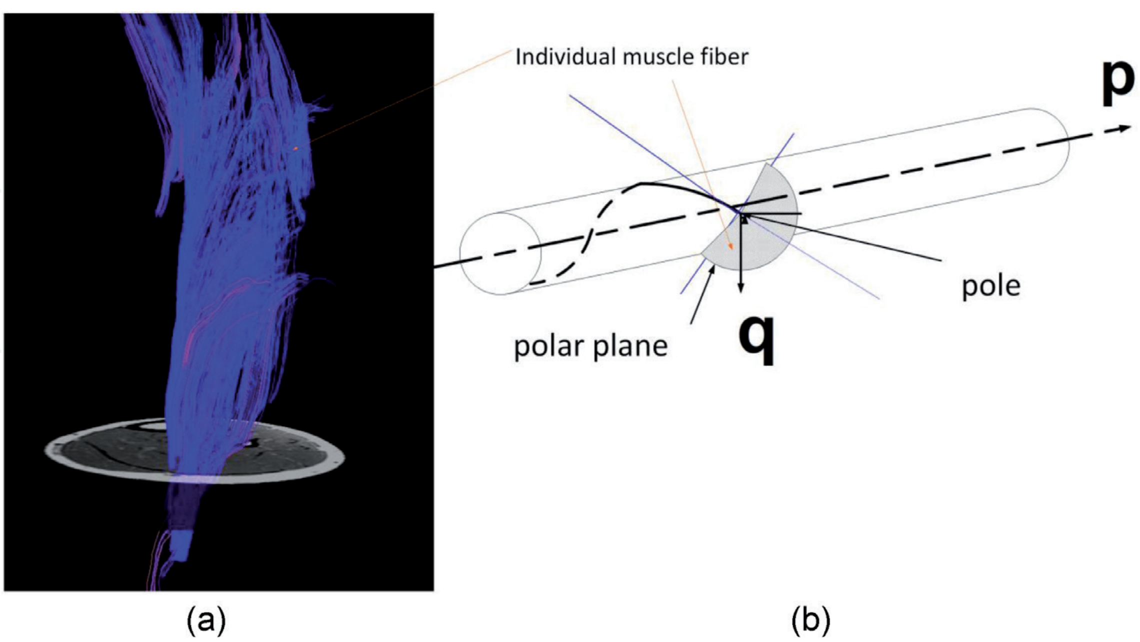

Figure 3.
(a) Fiber tractography image of a portion of the lateral gastrocnemius muscle as demonstrated in an exemplar healthy subject. The overlying images were generated at one region of interest, corresponding to the muscle boundaries where the anatomical cross-section area was maximal (whole-body MRI scanner, Signa HDxT 1.5 T, GE Healthcare, USA). The patients were placed in the supine position, feet first, and the position of each participant was considered in relation to the long axis of the leg, which was placed in parallel to the magnetic field. (b) a manifold of muscle fibers in tension forms to the linear complex identified as an instantaneous screw $IS(\mathbf{p})$ *and its perpendicular pole* ($\mathbf{q}$) *within the synergy of gait.*

cannot remain in equilibrium if the fiber forces that act upon the body have a non-balance resultant force. The velocity vector of every point in the fiber segment is tangential to the helix passing through it. The pattern of this velocity vector is a helicoidal velocity field. Each point that does not coincide with the screw's twist $IS(\mathbf{p})$ is referred to as a pole $(\mathbf{q})$. Associated with each pole is its corresponding polar plane. A polar plane and its corresponding pole, as defined by the instantaneous screw, have been illustrated here (**Figure 3(b)**).

In our previous research [42, 43], we introduced the concept of measurable invariant of the knee perceptual organ. In such invariant, six constraints ($) are collectively reciprocal to the instantaneous knee screw (IKS or $) indicated by ⊗ (**Figure 2(b)**). These metrics predicted the knee synergy model based on synergies [44]. Moreover, this perspective defines torque-free pure forces based on the tensegrity structure [45–48]. It is important to note that this configuration is a tensegrity configuration, as the system is pre-stressable in the absence of external forces, such as ground reaction forces during actual locomotion [49]. It was shown the knee tensegrity structure (KTS) has six constraints, and that it can balance the forces between tension and compression in the joint such that no work results

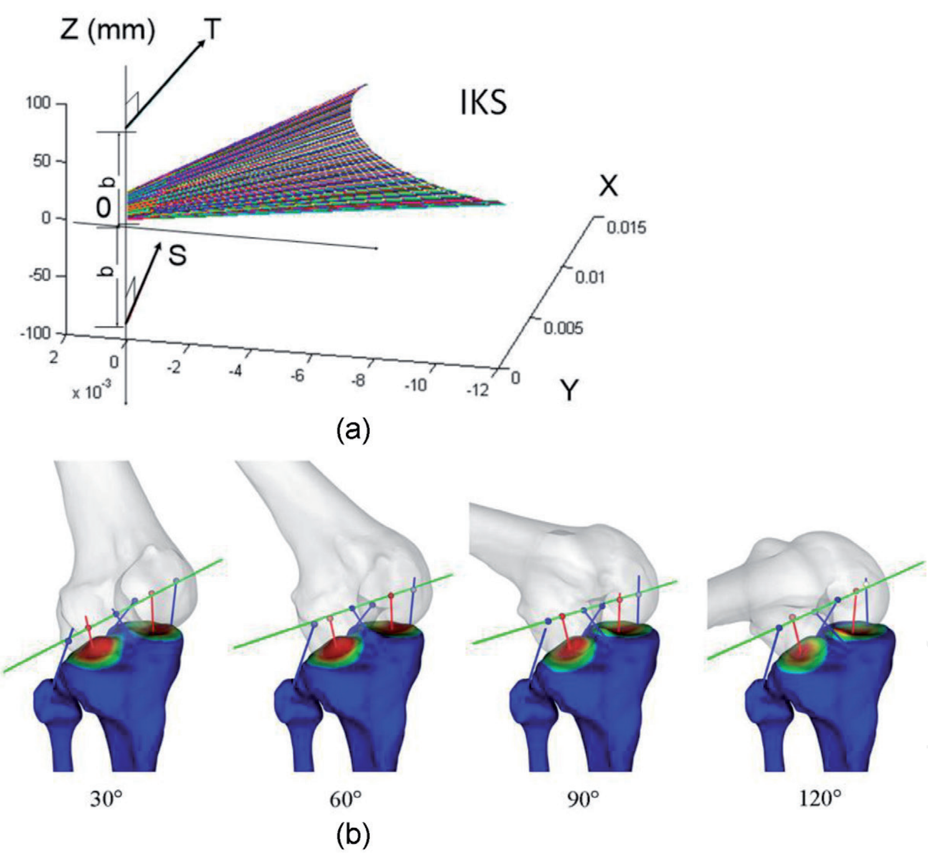

Figure 4.
(a) An exemplar Ball-Disteli diagram [52] with two generally disposed screws (T and S or $\mathbf{p}_1$ and $\mathbf{p}_2$), conveniently placed on the z-axis along their common perpendicular (with b). The origin of coordinate O is halfway between the screws, and the x-axis is inclined by half the included angle σ between the two screws (S, T). An instantaneous knee screw (IKS) after normalization is linearly dependent on the screws during any point of knee movement. The Ball-Disteli diagram aligns itself using the principle of three axes. (b) Representation of the IKS (green line); see Online Supplementary Video 1 (video is available via the following link: https://drive.google.com/file/d/18_YtszzT3_IvNIken5uxObj4jmSd0Zs_/view?usp=sharing). The lines of action of the ligaments (blue lines) and cartilage contact (red areas and red lines) for wrenches identified every 30° within the range of knee motion for a given patient. The white or colored dots represent the closest point to the IKS for each wrench. The colors range from white (di > 5 mm) to the color of the corresponding intersecting line (di = 0 mm). Cartilage contact colors on the tibia are proportional to the tibial-femoral relative separation (red: Distance ≤0 mm; blue: Distance >7 mm). The original anatomic schematics and lines of action were published previously [51] and are used by permission of professor Michele Conconi.

[50]. The KTS can be pre-stressed to obtain the same configuration as if external loads were applied. The selected pre-stress may yield the same configuration in the swing phase (external forces are absent) as in the stance phase (external forces are present) [49]. Notably, preparedness is not only a reactive aspect of the movement apparatus, but it also relates to anticipatory adjustments that predispose a system to behave in a particular way [37].

If a knee joint is only free to twist about a screw IKS while in equilibrium, despite being acted upon by the fiber reaction, the mechanical work during a small displacement against the reaction forces $\$'$ in the KTS must be zero, according to the following relationship [40],

$$\$^{T} \cdot KTS = 0 \tag{1}$$

Uniform motion transmission between two axes (defining the thigh and shank, respectively) is affordable only if their lines of action pass through the IKS, as expressed in the Eq. (1). Thus, the affordances of the knee synergy must be positive, and the joint ligaments should remain in an isometric/isokinetic condition or continuous length/tension. If not, the ligaments become slack or loose, resulting in roof impingement, post-reconstruction [5]. Moreover, Eq. (1) also implies that the moving self ($) and the invariant structure of the KTS reaction are reciprocal aspects of the same perception. Gibson called this information gathering approach propriospecific, as opposed to exterospecific, to specify the observer (here the self) as distinguished from the environment.

The knee synergy approach proposed herein was recently validated experimentally [51]. The authors calculated if all the lines of action intersect at the IKS ($) following natural knee motion to describe the knee surgery invariant. The results show the mean distances between each constraint line of action, and the IKS stayed below 3.4 mm and 4.5 mm for *ex vivo* and *in vivo* assessments, respectively (**Figure 4(b)**).

5. The affordance-based design applied to graft placements during reconstruction

It has been hypothesized that a tensegrity system serves the medium of haptic perception, from the individual cells to the whole body, maintaining continuous tension and discontinuous compression [53], which clearly exhibit the determinate character of the entire body system perception [38, 40]. In this study, we present the positive affordance-based design on graft placement while in continuous tension, rather than designing against the negative affordance by preventing impingement. As described, we use the invariant structure of the KTS [54] as an appropriate ecological frame of reference to locate the tibial tunnel placement. For the ACL-patient to engage the IKS directly, clinicians have to measure the tunnel placement relative to the posture and behavior of the person being considered, making continuous graft tension possible. First, an invariant should not be applied to the patient directly, for it is not a stimulus. Second, invariants can be considered qualitative rather than quantitative so that other clinical assessments can make it available to their surgeons/observers in an exact mathematical description [14].

The IKS is defined in terms of the second-order invariant by a linear combination of the two screws of the first-order invariant, *S* and *T*, instantaneous screw axes of the shank and thigh (**Figure 4(a)**) [55]. Then the IKS must be a screw that has been picked up from the many candidate screws on the cylindroids [40], which is reciprocal to KTS (via Eq. 1). Hence, the ratio of the amplitudes about *S* and *T* may be determined (**Figure 4(a)**), which manifests the fact that the sensitivity of the knee joint to its disposition is of crucial importance in picking up information.

Two lines were projected respectively to the sagittal plane so that the path of the graft could be aligned to any transversal axis intersecting the IKS ($), the central line of KTS that is the second-order invariant line, also called the IKS (**Figure 1(a)**). The lines were generated at full knee joint extension. Notice that if the graft line is not precisely aligned with the member line within the KTS, due to position errors, for example, the velocity difference on the graft line would not be zero, but would still be small. If the path of an ACL graft is so selected that it cuts the IKS of the KTS, then the line becomes a member of the KTS, which ensures the isokinetic graft placement related to trans-tibial-femoral tunneling. Consider now the necessary kinematic relations in that contact point c as the common point belonging to both the tibial and femoral tunnels (**Figure 1(a)**).

The velocity of the point c residing on the femoral tunnel (V_F) can be resolved into two components: one component is perpendicular to the graft line and the other element parallel to it. Similarly, the velocity of the point on the tibial tunnel coincident with point c (V_T) can also be resolved into two components. For the two bony bodies (femur and tibia) to remain through one continuous body, the parallel component of the graft line for velocity must be equal, by projecting V_F and V_T onto the graft line (**Figure 1(a)**). The graft without that qualification would experience impingements. The difference in the perpendicular component represents the relative transverse velocities between the articulating tunnels and is closely related to an essential factor in choosing the proper tunnel width. Widening of the tunnel diameter might be performed, allowing more tolerance for this transverse velocity relationship, taking into account the width of the graft and the existing diameter of the notch.

As described, we identified the measurable second-order invariant of knee synergy and proposed it as a new view of the basis of tunnel placement by using Eq. (1). The knee synergy approach identifies the information as a means to perceive the affordance of uniform motion transmission. To apply the described approach and identify the invariant, we characterized the shank to the thigh (the tibia to the femur) relative motion, i.e., the second-order invariance of the knee synergy. These results were then compared with experimental data for validation as provided by the “Grand Challenge Competition to Predict *In Vivo* Knee Loads” as part of the Symbiosis project funded by the National Institutes of Health [56].

6. Entrainment of touch and posture

Contrasting the established idea of senses, Gibson considered separate anatomical units as perceptual systems [29]. In the present case, a joint yields spatial information, skin-nerve conveys contact information, and in certain dynamic combinations, joint and skin-nerve yield synchronization, or entrainment specifying information about the layout of external surfaces during locomotion.

Behavioral dynamics in a consistent approach has proposed to account for the dynamics of perception and action [57]. This approach followed Gibson’s idea that rather than being localized in an internal (or external) structure, control is distributed over the agent-environment system, in the present case, the user-artifact-surface system. Therefore, Warren’s behavioral dynamics argues for a one-to-one correspondence between the internal structure IKS, constituted by the internal forces formed by the distal end of the femur and the proximal end of the tibia, and the external structure, represented by the ground reaction forces (GRFs) on foot [58].

Behavioral dynamics control laws indicate that the entrainment or coordination of shank and thigh (S, T) follows the same physical laws as the entrainment between the knee and ground (IKS, GRF). Therefore, the cross-ratio [59] of the ordered pair (IKS, GRF) with respect to the ordered pair (S, T) is

$$\{(IKS, GRF);(S, T)\} = -1. \tag{2}$$

For a given IKS (when an observer perceives the affordance of the surface) and the location of the center of pressure (COP) on the axis of the GRF is known, then the GRF vector is limited to a plane in the screw system of the first order [47, 48] (**Figure 5(a)**). The muscle synergy η and GRF φ are then compounded into an invariant, limited to the plane of the COP in reciprocity with the IKS. This theorem was originally proposed by Möbius, who showed that forces from six lines could be equilibrated, and also, if five of the lines are given along with a point on the sixth line, then the sixth line is limited to a polar plane [40].

To test such ecological approach to perception and action during the stance phase of a gait, we compared previously published experimental data sets [56] with our predicted datasets [47, 48] in terms of medial and lateral contact forces. Available data included limb motion capture, fluoroscopy images, GRFs, electromyographical readings determining muscle forces, as well as medial and lateral knee contact forces derived from GRFs. Data were collected from an adult male with a right knee reconstruction (65 kg mass and 1.7 m height). When the variations in the ground contact (magnitudes and direction) were shown along with the variations of knee movement in terms of IKS, an invariant was determined uniquely by the two corresponding pairs, see Eq. (2) (**Figure 5(b)**).

In this study, the IKS was determined by a linear combination of two instantaneous screw axes of the shank and thigh (**Figure 4(a)**). The IKS nearly coincides with a reciprocal screw of the GRF, as indicated in a magnified inset image in **Figure 5(b)**. A perceptual system of the knee can come to equilibrium since twists of amplitudes S and T neutralize. We thus see that the evanescence of one

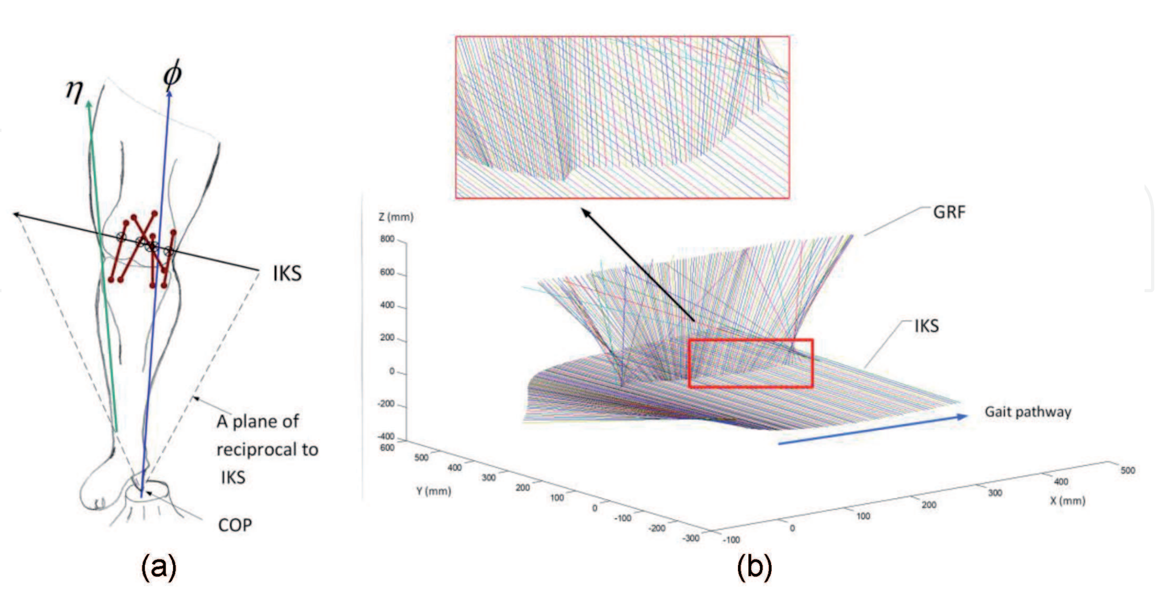

Figure 5.
(a) The framework for estimating responses to constraints on the knee joint (ligament forces and contact forces) is influenced by the inclusion of muscle synergy (η) and GRF (φ) relative to the center of pressure (COP). The judicious generation of the IKS for the one DOF in knee equilibrium simplifies the estimation. This figure was adapted from the original figure published previously [47, 48]. (b) Perception and action during the stance phase of gait entrain the knee joint rotation with the touch pattern (GRF) of the foot. The invariant knee-manifolds demonstrates that an affordance for postural stability is measured relative to the posture of the patient, as represented by the entrainment of the GRF with the IKS at any point in the gait pathway.

function must afford all that is necessary for subordinate organs (S, T) belong to an IKS of the superordinate organ for information pickup over paths of locomotion. This reciprocity is captured by the concept of a mutual relationship between the constraints and the DOF [60, 61]. Information about the person accompanies information about the environment. Here it is shown that proprioception accompanies exteroception; information is available to specify both poles [14].

A lateral radiograph of the knee in extension was the traditional approach to diagnose any roof impingement, and a portion of the tibial tunnel was traditionally placed anterior to the intercondylar roof [5] (**Figure 1(b)**). However, the available information on the experimental images can not be applied to another patient because they do not provide environmental information. Thus, AUA has the potential to diagnose pathologies. The last decade has seen a paradigm shift in the measurement of clinical outcomes, with an increasing focus on the user's perspective, PROMs. Many clinicians, though, are less confident in self-reported PROMs, than in 'objective measurements' [11]. Recent studies identified several sensations, activities, and psychological factors such as feelings of instability and knee-related fears that make the patients aware of their artificial knee joint [62]. They concluded that joint awareness might work as an overarching parameter. This is aligned with Gibson's statement that an affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy [14]. Affordances have to be designed in relation to the uniqueness of each patient, and thus posture and movement need to be measured in terms of a specific patient-environment system, not in patient-centered terms.

7. Conclusion

This study presented an affordance based design supporting knee reconstruction surgery, with applications to the user/surgeon/therapist. It brings ecological theory to robustly explain knee biomechanics and clarifying the general role of physical artifacts and affordances in surgery. The mutuality of user and artifact that we defended here is not traditionally guiding individualized ACL reconstruction. Instead, the anatomic ACL reconstruction seems to lead to the idea that a deficient ACL is not understandable within knee joint biomechanics [32]. As we argued, the ACL is a highly organized synergy with intra- and extra-articular components [34] and yet still an identifiable system within the anatomic environment. The knee complexes in Eq. (2) reinforce how perception and action are coupled. A unique combination of invariants, a compound invariant, is just another invariant [14]. In particular, this study identified the knee complexes as the measurable invariable structures that specify the persisting placement of the tunnel during ACL reconstruction.

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