Journal of Biomechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Contact forces in the tibiofemoral joint from soft tissue tensions: Implications to soft tissue balancing in total knee arthroplasty

Matthias A. Verstraete [a,b,*], Patrick A. Meere [b], Gaia Salvadore [b], Jan Victor [a], Peter S. Walker [b]

[a] Ghent University, Gent, Belgium
[b] New York University, Langone Medical Center, Laboratory for Orthopaedic Implant Design, New York, United States

ARTICLE INFO

Article history:
Accepted 8 May 2017
Available online xxxx

Keywords:
Total knee arthroplasty
Intra-articular loads
Load balancing

ABSTRACT

Proper tension of the knee's soft tissue envelope is important during total knee arthroplasty; incorrect tensioning potentially leads to joint stiffness or instability. The latter remains an important trigger for revision surgery. The use of sensors quantifying the intra-articular loads, allows surgeons to assess the ligament tension at the time of surgery. However, realistic target values are missing. In the framework of this paper, eight non-arthritic cadaveric specimens were tested and the intra-articular loads transferred by the medial and lateral compartment were measured using custom sensor modules. These modules were inserted below the articulating surfaces of the proximal tibia, with the specimens mounted on a test setup that mimics surgical conditions. For both compartments, the highest loads are observed in full extension. While creating knee flexion by lifting the femur and flexing the hip, mean values (standard deviation) of 114 N (71 N) and 63 N (28 N) are observed at 0° flexion for the medial and lateral compartment respectively. Upon flexion, both medial and lateral loads decrease with mean values at 90° flexion of 30 N (22 N) and 6 N (5 N) respectively. The majority of the load is transmitted through the medial compartment. These observations are linked to the deformation of the medial and lateral collaterals, in addition to the anatomy of the passive soft tissues surrounding the knee. In conclusion, these findings provide tangible clinical guidance in assessing the soft tissue loads when dealing with anatomically designed total knee implants.

1. Introduction

Total knee arthroplasty involves critical interaction with the soft tissues surrounding the knee to obtain a stable, well-functioning joint following surgery. The tension in these soft tissues controls the boundaries of laxity. At any angle of flexion, the soft tissues' effect is determined by their initial tensions and their stiffnesses. After a total knee arthroplasty (TKA), achieving normal laxity and stability during function is an important consideration, made more difficult due to the resection of one or both cruciate ligaments in most total knee designs. This problem is evident because instability can lead to increased polyethylene wear (Kretzer et al., 2010) and remains an important reason for early failure after TKA surgery, responsible for 17–26% of the early revision surgeries (Dalury et al., 2013; Lee et al., 2014). These numbers are not surprising, given the complexity in compensating for the alteration and loss of stabilizing structures during insertion of the implant. Simultaneously, a correct component alignment needs to be assured (whether kinematic or mechanical is still under debate (Cherian et al., 2014)), taking into account cartilage wear and potential deformity in the bone morphology. A large number of variables are thus involved in this process: implant design, surgical technique, soft tissue tensioning and component positioning (Walker et al., 2014). This paper focuses on the soft tissues surrounding the articulating surfaces, consisting of purely passive structures (e.g. capsule and ligaments) and combined active-passive restraints (e.g. tendons and muscles).

Dominated by the ligaments, the soft tissues control the passive stability of the knee joint (Blankevoort et al., 1991; Halewood and Amis, 2015). As a result, the degree of (in)stability can be assessed at the time of surgery by evaluating the tension in and/or strain of the ligaments. Although results have been published in the literature, a direct evaluation of the ligament strain remains impractical in a surgical setting (Fleming et al., 2003). Alternatively, the ligament tension can be indirectly assessed by evaluating the contact loads in the tibiofemoral joint. More specifically, the load transferred through the medial and lateral compartment can be quantified using sensors that quantify the forces exerted by the femur at

* Corresponding author at: De Pintelaan 185, 13K12, 9000 Gent, Belgium. Fax: +32 9 332 49 75.
E-mail address: Matthias.Verstraete@UGent.be (M.A. Verstraete).

http://dx.doi.org/10.1016/j.jbiomech.2017.05.008

Please cite this article in press as: Verstraete, M.A., et al. Contact forces in the tibiofemoral joint from soft tissue tensions: Implications to soft tissue balancing in total knee arthroplasty. J. Biomech. (2017), http://dx.doi.org/10.1016/j.jbiomech.2017.05.008

the level of the tibia. In the remainder of this paper, these loads are referred to as compartmental loads. Such approach has the advantage of additionally accounting for the tension created by other structures (e.g. capsule) and not narrowing down to tension in a (discrete) number of ligaments.

Nowadays, these compartmental loads can be assessed intraoperatively, for instance by using instrumented tibial trial components that quantify the tibiofemoral contact forces at the level of the tibia. Use of these sensors has the potential to restore physiological load balance and increase patient satisfaction following TKA surgery (Gustke et al., 2014a,b). Literature recommends compartmental load levels in the range of 90–180 N (20–40 lbs), with a constant magnitude through the flexion-extension range (Asano et al., 2004) and a limited load difference between the medial and lateral compartment (<67 N/15 lbs) (Gustke et al., 2014a,b). However, a fundamental basis for the identification of these target load levels is missing. In an attempt to identify loads that are representative of the native anatomical situation, this study presents a quantitative assessment of the compartmental load levels in a series of cadaveric non-arthritic knees.

2. Methods

2.1. Test specimens

A total of eight fresh frozen cadaveric specimens was used. The specimens consisted of full lower limbs including a hemi-pelvis. Prior to inclusion, the knees were assessed for osteoarthritis using X-rays. Only specimens with a Kellgren-Lawrence score below grade 2 were selected (Table 1). Three additional specimens were used for method development and data from a forth additional specimen was discarded because the sensor described below failed during testing.

2.2. Test setup

The full lower limb specimens, from pelvis to foot, were mounted in a custom test setup (Fig. 1) that aims at mimicking surgical conditions. Therefore, muscle activation was not considered.

The test setup primarily aimed to provide full kinematic freedom to the knee. In that respect, the pelvis was first fixed to the base of the setup by means of an adjustable frame supplemented by two pins drilled through the ilium. Femoral axial rotation and ab/adduction of the hip was subsequently prevented by a single sagittal anchoring pin that attached the femur to an outrigger arm solely allowing for unimpeded rotation around the mediolateral axis of the hip joint. Consequently, the three degrees of freedom of the hip joint were reduced; only the flexion-extension of the hip remained unrestrained (R_1) by the outrigger arm. Minimal disturbance by friction was thereby assured through the use of roller bearings.

The tibia was rigidly connected to a U-shaped frame by means of two distal pins. This U-shaped frame was subsequently connected to the base of the test setup by means of three distinct bearings. A first rotational, three degrees of freedom ball-in-socket bearing connected the U-shaped frame to a mobile platform. This platform is mounted on two perpendicular axial roller bearings that allowed unrestrained translation in the mediolateral and proximal-distal direction. This resulted in five degrees of freedom for the tibia:

- R_2: rotation around the mediolateral axis of the tibia (flexion/extension rotation).
- R_3: rotation around the mechanical axis of the tibia (internal/external rotation).
- R_4: rotation around the anterior-posterior axis of the tibia (varus/valgus rotation).
- T_1: translation along the proximal-distal direction.
- T_2: translation along the mediolateral axis of the tibia.

In total the knee holds six degrees of freedom (5 + 1). To flex and extend the knee, either the femur was rotated clockwise in the R_1 direction by lifting the outrigger frame or, the ankle was moved along the T_1 direction by pushing the carriage mounted on the axial roller bearings. In the remainder of this paper, the former is referred to as the thigh pull test, the latter is addressed as the heel push test. These boundary conditions introduce some significantly different externally applied loads to the knee (Appendix B) (Plagenhoef et al., 1983).

2.3. Evaluation of loads and kinematics

2.3.1. Installation of load sensors

Load sensors were installed below the articulating surfaces of the tibiofemoral joint, similar to the location presented by Singerman et al. (1999). In our paper, however, these loads were measured both at the medial and lateral compartment by a custom sensor module (Fig. 2). This module contained two 3D printed shims and a Tekscan type 4011 pressure sensor (Tekscan Inc, Boston, Massachusetts, USA). The contours of the shim on top of the module were shaped in accordance to the anatomical cross section of the tibia, taking into account the size and side of the tested specimen. The undersurface of this upper shim contained two rectangular zones of increased height located at the center of the medial and lateral side. The two sensing zones of a Tekscan pressure sensor type 4011 were firmly fixed to these zones of increased height. At its inferior base, the module was closed by a flat 3D printed shim. Both shims were created using a MakerBot Replicator printer using PLA filament (MakerBot Industries, Brooklyn, New York, USA). Following the assembly of this module, the sensors were calibrated yielding the medial and lateral compartmental loads. This resulted in a relative error between the actual and measured force below ±13.1% within the range of interest, as detailed in the sensor module calibration procedure (Appendix A) (Li et al., 2006; Pinskerova et al., 2004).

The preparation of the specimen was performed by an experienced knee arthroplasty surgeon (PAM). In preparation for the testing, a standard sub-vastus medial arthrotomy was performed, followed by subperiosteal elevation of the medial proximal tibia to the level of the tibial tubercle. A complete transverse tibial slot was created using an oscillating saw with a rigid 1.5 mm thick blade. This slot was perpendicular to the mechanical axes of the tibia and located at a height approximating the level of bone resection performed in TKA surgery (e.g. 8 mm below the lowest point). The capsule was preserved in its integrity for a minimum of 270° of the perimeter of the proximal tibia. This is demonstrated by the intact lateral skin margins in Fig. 2c. Fig. 2a demonstrates the match with the shim after completion of the experiment. Great care was exercised to cut the bone with the oscillating saw up to a few millimeter of the capsular edge without transecting the periosteal membrane, as typically done in a proximal tibial osteotomy. The residual marginal bony attachment was carefully curetted. This method allowed for complete resection of the bony content of the created gap, yet with confident preservation of the non-obstructive extra-osseous periosteal hinge from the tibial tubercle to the lateral side, posterior side, and posteromedial corner. Only the anteromedial corner of the proximal metaphyseal tibial periosteum was incised from the tibial tubercle to the anterior portion of the deep medial collateral ligament. This opening was meticulously repaired with non compressive sutures (2–0 fiberwire) over drill holes

Table 1
Demographics of tested specimens.

Specimen number	Age [y]	Length [m]	Weight [kg]	BMI [kg/m^2]	Sex [–]	Side [–]	Data included
1	67	1.85	84	24.5	M	R	No[a]
2	70	1.78	83	26.2	M	R	No[a]
3	67	1.73	50	16.7	M	R	No[a]
4	77	1.88	79	22.4	M	R	Yes
5	76	1.73	64	21.3	M	R	Yes
6	70	1.80	79	24.4	M	L	Yes
7	59	1.65	69	25.1	M	R	Yes
8	73	1.70	55	19.0	M	R	No[b]
9	55	1.75	50	16.3	M	R	Yes
10	55	1.73	50	16.7	M	R	Yes
11	84	1.75	50	16.3	M	R	Yes
12	64	1.80	49	15.1	M	R	Yes

[a] Test used for method development.
[b] Sensor broke during testing.