



## Optimizing TKA Positioning via Intraoperative Ligament Characterization

Alexander D. Orsi PhD<sup>1</sup>, Edgar Wakelin PhD<sup>2</sup>, Sami Shalhoub MS<sup>2</sup>, Jeffrey M. Lawrence MD<sup>3</sup>, Corey E. Ponder MD<sup>4</sup>, John M. Keggi MD<sup>5</sup>, and Christopher Plaskos PhD<sup>2</sup>

<sup>1</sup> Corin Australia, Sydney, New South Wales, Australia  
alex.orsi@coringroup.com

<sup>2</sup> Corin U.S.A, Raynham, Massachusetts, U.S.A.  
edgar.wakelin@coringroup.com  
sami.shalhoub@coringroup.com  
christopher.plaskos@coringroup.com

<sup>3</sup> Gundersen Health System, Viroqua, WI, U.S.A

<sup>4</sup> Department of Orthopedic Surgery and Rehabilitation, University of Oklahoma Health Sciences Center, Oklahoma City, OK, U.S.A

<sup>5</sup> Orthopaedics New England, Middlebury, CT, U.S.A

### Abstract

The goal of total knee arthroplasty (TKA) is to position the prosthesis with a balanced soft tissue envelope throughout the flexion cycle. Determining a desirable amount of ligament tension is crucial as instability is a leading cause for revision surgery. This is challenging due to the subject specific, and non-linear, nature of ligament mechanical properties. This study aims to characterize ligament stiffness profiles intraoperatively and identify the stiffness transition point (STP) using a ligament balancing robot. The study will also identify how the surgeon selected joint force relates to the stiffness transition point.

45 patients were reviewed. After the proximal tibial resection, intraoperative assessment of the medial and lateral ligaments was performed via a load cycle ramped up from 50N to 120N, then down from 120N to 50N. This was performed at extension (10°) and in flexion (90°). Force and displacement data were processed to determine the stiffness profiles for the medial and lateral soft tissue envelope. A bilinear fit model was used to determine the slopes and STP.

The average STP was between 83N and 90N, varying widely with standard deviations approaching 14N. The median joint tension selected by the surgeon was 80N. On average the selected joint force was 3N to 8.9N below the STP.

The medial compartment behaved similarly in extension and flexion. The lateral compartment had higher stiffness in extension than in flexion. Across all loading conditions, the down-cycle data was more consistent than the up-cycle data.

The STP is a proposed target for ligament tension as this theoretically avoids the high stiffness regime. The results show the joint tension selected by the surgeons, based on their experience and intraoperative feel, is similar to the STP. Due to the high patient variability

observed in the STP, using a patient specific method to determine the joint tension is recommended. Future work will investigate how joint tension relative to the STP affects patient outcomes. This will provide insight into optimizing joint tension during TKA.

## 1 Introduction

Determining a desirable amount of ligament tension is crucial for total knee arthroplasty (TKA) as instability is a leading cause for revision surgery [1, 2, 3]. Little data exists on optimizing joint space tension during TKA. Traditionally surgeons use manual devices to assess joint space tension. A downside to this is that no prescribed force is targeted. This requires the surgeon to operate based on what force “feels” adequate for the joint space [4].

Ligament behaves as a piece-wise, non-linear visco-hyperelastic material. During axial loading it initially behaves as a non-linear material (toe region) as the collagen fiber network uncrimps. With increased load, the collagen fibers align and the ligament transitions to a linear material [5]. The point at which this behavior change occurs is defined as the stiffness transition point (STP). Ligament properties are subject specific, varying widely based on factors such as sex, BMI and age [3, 6]. This study aims to characterize ligament stiffness profiles intraoperatively to identify the STP. The study will also compare how the surgeon selected joint force relates to the STP.

## 2 Methods

45 patients were assessed by 2 surgeons at 2 centers. After the proximal tibial resection, and prior to femoral resection, an intraoperative assessment of the medial and lateral ligaments was performed using a digital joint tensioning device (BalanceBot<sup>TM</sup>), seen in Figure 1a. A load cycle was applied independently to both the medial and lateral compartments, ramped up from 50N to 120N, then down from 120N to 50N. This was performed at extension (10°) and in flexion (90°). 10° was chosen in extension to avoid posterior capsule tightening and to isolate the medial and lateral structures. The surgeon then selected a force value to apply to the joint space based on intraoperative feel, and finished the procedure. Force and displacement data was processed to determine the stiffness profiles for the medial and lateral soft tissue envelope in both flexion and extension. A bilinear fit model was used to determine the slopes and stiffness transition points (STP). While it is known that the initial behavior of ligament is non-linear, this fitting process was used to keep consistency with previous work performed by Hesterbeek et al [2]. The average differentials between the STP and the surgeon selected joint force were also calculated.

## 3 Results

Slope 1 refers to the initial low stiffness region, while Slope 2 refers to the high stiffness region. Figure 1b provides stiffness profiles from an example patient. The STP is the force value at the intersection point of the two slopes. The average STP ranged between 83N and 90N across all loading conditions, seen in Table 1. High variability was observed for the STP with standard deviations as high as 14N. Across all testing conditions, the STP showed greater consistency during down cycle loading compared to up cycle loading.

The median surgeon selected joint tension was 80N. 24 patients were implanted with 80N, 18 patients were implanted with 90N, and one patient was implanted with 100N of joint tension.

Load Condition			Slope 1 ( $N/mm$ )	Slope 2 ( $N/mm$ )	$R^2$	STP ( $N$ )	Differential ( $N$ )
Extension	Medial	Up	22.7(11.9)	30.7(14.7)	0.9690	89.8(13.1)	-8.9(22.7)
		Down	26.7(11)	55.7(27.8)	0.9791	87.6(10.9)	-6.7(20.7)
	Lateral	Up	18.3(23.9)	30.3(15.6)	0.9845	86.6(13.5)	-5.8(22.2)
		Down	26.5(12.4)	61.8(31.2)	0.9824	85.2(11)	-4.3(22)
Flexion	Medial	Up	24.2(11.7)	29.2(9)	0.9894	87.6(11)	-6.7(22.1)
		Down	23.3(6.9)	50.5(11.9)	0.9661	83.9(7.9)	-3.0(16.6)
	Lateral	Up	20.2(21)	17.3(8.2)	0.9870	88.6(14)	-7.7(23.5)
		Down	15.8(6.9)	40.7(20.6)	0.9613	83.8(10)	-3.0(22.1)

Table 1: Stiffness results

Joint tension data was not recorded in two patients. The differential data shows on average the selected joint force was  $3N$  to  $8.9N$  below the STP in all loading conditions.

In extension, the average medial compartment stiffness (up-cycle/down-cycle) of Slope 1 was  $23/27N/mm$  with a Slope 2 of  $31/56N/mm$ . In flexion, the medial compartment stiffness of Slope 1 was  $24/23N/mm$  with a Slope 2 of  $29/51N/mm$ .

In extension, the average lateral compartment stiffness of Slope 1 was  $18/27N/mm$  with a Slope 2 of  $30/62N/mm$ . In flexion, the average lateral compartment stiffness of Slope 1 was  $20/16N/mm$  with a Slope 2 of  $17/41N/mm$ .

Slope 1 was most consistent in flexion on the down cycle with standard deviations of  $6.9N$  and  $6.9N$  for the medial and lateral ligament respectively. Slope 2 was most consistent in flexion on the up cycle with standard deviations of  $9N$  and  $8.2N$  for the medial and lateral ligament respectively.

## 4 Discussion

The STP is a proposed target for ligament tension as this theoretically avoids the high stiffness regime [7]. The surgeon selected joint force was on average below the STP, indicating the surgeons may already be targeting the STP region, and avoiding the high stiffness regime. It should be noted that Heesterbeek et al. 2017 reported a lower range for the STP, between  $48N$  and  $59N$  [2].

The medial compartment behaved similarly in extension and flexion. The lateral compartment showed a reduction in stiffness from extension to flexion. For all loading conditions Slope 1 had lower standard deviations during down cycle loading compared to up cycle. Conversely, for all loading conditions Slope 2 had lower standard deviations during up cycle loading compared to down cycle.

The calculated STP had reduced variability when using down cycle data compared to the up cycle data. This was expected due to ligament creep. Future BalanceBot<sup>TM</sup> studies should continue to use down cycle data. The flexion data was also more consistent than extension data. Future work is needed to improve extension data collection techniques.

One limitation is the use of a bilinear fit to determine the STP, ignoring the non-linear regime of ligament. Also, the stiffness profiles in some cases were not ideal, showing considerable variability. This could be due to anatomic anomalies, surgeon experience, as well as surgeon technique.

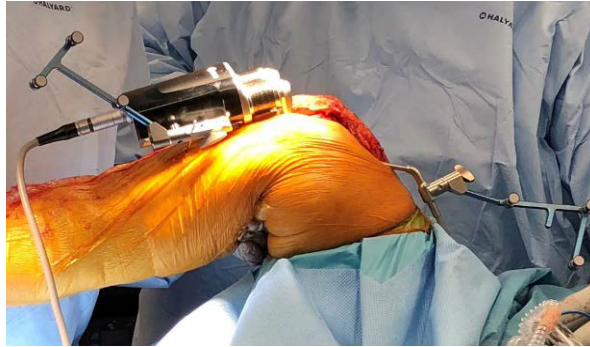
It remains unknown whether the STP is an optimal target. High variability was observed in

the STP from patient to patient. However, the differentials between the STP and the final joint force were consistent. This result shows that quantifying the patient specific soft tissue profile can assist in determining a target load for the joint space. This work is novel as it is the first study to use intraoperative soft tissue data in extension and flexion to help guide prosthesis implantation.

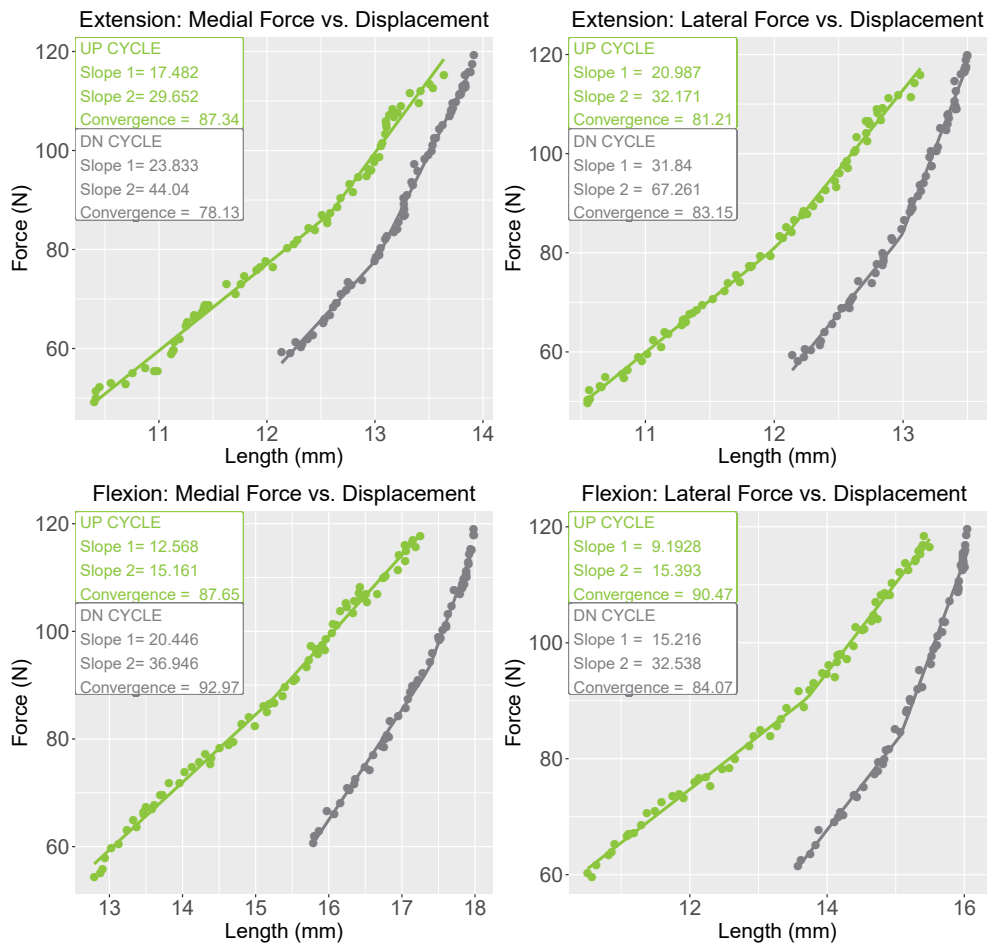
Future work will investigate how joint tension relative to the STP affects patient outcomes. This will provide insight into optimizing joint tension during TKA.

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(a) BalanceBot™ system.



(b) Stiffness profiles from an example patient.

Figure 1: BalanceBot™ system and example stiffness profiles. The gap in data between the up and down cycles is due to ligament creep. This occurs due to the time taken to switch between the cycles.