SMART COLLATERAL LIGAMENT BALANCER FOR INTRA- AND POSTOPERATIVE MEDIOLATERAL BALANCE

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Abstract: The poor ligament balance performed at the time of total knee arthroplasty (TKA) can cause postoperative instability and consequently early loosening of the prosthetic knee. The improper intraoperative assessment of ligamentous balance is due to the use of an accurate surgical instrument which tenses the medial and lateral collateral ligaments in uncontrolled way. A smart ligament balancer is proposed in this paper to assess and perform ligament balancing intra- and postoperatively. A detailed three-dimensional model of the prototype is developed using CAD software in order to discuss the operation of this device. The intraoperative use of this balancer could allow to accurately reestablish a rectangular tibiofemoral gap with symmetric mediolateral load distribution across the whole range of knee flexion. On the other hand, the implanted balancer could be used postoperatively to assess ligamentous balance and to correct it when needed.

1 INTRODUCTION

In most arthritic knee joints undergoing total knee arthroplasty (TKA), some degree of collateral ligament imbalance exists (Griffin, 2000). The ligament imbalance could be present in the form of instability, deformity, or a combination of these two elements. The importance of acquiring proper ligament balance at the time of TKA is well recognized (Insall, 1993). Many techniques have been used to assess ligament imbalance including knee tensioning devices (Laskin, 1989), spacer blocks (Insall, 1984), and manual distraction instruments. The aforementioned techniques balance the medial and lateral collateral ligaments by loading them with maximally or in uncontrolled way. If the resultant gap is trapezoidal, then the ligaments are imperfectly balanced. Moreover, the traditional tensors are unable to accurately assess the ligamentous balance because of the discrete measurement of tibiofemoral forces (Attfield, 1994). A robotized distractor (Marmignon, 2004) has been developed to assess soft-tissue balance. This distractor consists of a base plate which is connected with two independent and parallel trays. The upper trays support the condyles and can be lifted by means of a jack and a cable or thanks to two inflatable rubber bladders. The disadvantage of the first approach is that the device is not powerful enough (maximal force is equal to 100 N), while the disfavor of the second is that the parallelism of upper trays could not be assured, which influences the right functioning of the device. A force-sensing device (Crottet, 2005) has been developed to intraoperatively enhance the ligament balancing procedure. This device has two sensitive plates to support the two femoral condyles, a tibial base plate and a set of different size spacers to fit the apparatus thickness to the patient-specific tibiofemoral space. Each of the two sensitive plates is instrumented with three deformable bridges. Each bridge is equipped with thick-film piezoresistive sensor to ensure the accurate measurement of the amplitude and location of tibiofemoral contact forces. The soft-tissue imbalance is then assessed by the net varus-valgus moment. The major limitation of this device is that the application of load is manually performed by stressing the lower limb, thus load is difficult to be accurately applied. Moreover, the augmentation of tibiofemoral gap height and consequently ligament tension must be achieved by inserting different size spacers, which increases the time and complexity of TKA.

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To address the aforementioned shortcomings, a smart ligament balancer is proposed to assess and balance the collateral ligaments intra- and postoperatively and to correct the imbalance when needed.

2 MATERIAL AND METHODS

A detailed three-dimensional model (Fig. 1) of the device is designed using CAD software in order to describe the functionality of this device. The proposed device consists of a fixed base plate and two mobile plates. The lower base plate is separately connected to each of the top plates by a scissor mechanism operated by a miniature linear actuator.

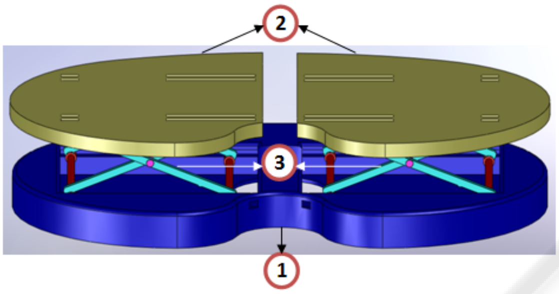

Figure 1: An Isometric view of the smart ligament balancer: 1. the fixed tibial base plate, 2. the two mobile plates, and 3. the two scissor mechanisms.

The actuator located at the bottom of base plate compartment drives one sliding shaft away from the other in order to move the upper plate downward and vice versa (Fig. 2). The two actuators are automatically driven by a microcontroller in response to the command signals sent by the surgeon and to the force and position values measured by adequate sensors embedded into the device. The device is equipped with force and position sensors. Three force sensors are embedded within each mobile plate to continuously measure the amplitude and location of the corresponding compartmental contact force. One position sensor is embedded into each compartment of the base plate to accurately measure the distance between both the upper plates and the lower plate at any time of the balancing procedure.

In our study, the perfect ligament balance is defined by a rectangular tibiofemoral gap and a symmetric distribution of compressive load between the medial and lateral compartments of knee at both full extension and at 90° of flexion. The purpose of this study is to assess the soft tissue balancing per- and postoperatively for the full range of knee motion and to rectify the imbalance when existed by means of smart knee balancer.

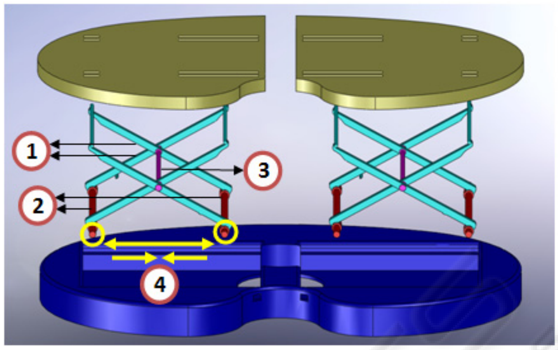

Figure 2: Exploded view of the smart ligament balancer: 1. the scissor arms, 2. the sliding shafts, 3. the pivot shaft, and 4. the distraction and contraction of the actuator.

The immobile lower base plate of smart ligament balancer is positioned onto the proximal cut of the tibia while the two mobile upper plates are in contact with the corresponding femoral condyles. The balancer must be introduced into the tibiofemoral space after the tibial osteotomy is performed and before the femoral cuts are made. Measurement must be made at full extension with the smart balancer fixed onto the proximal tibial cut and acting against the distal femoral condyles and at 90° of flexion using the posterior femoral condyles and the proximal tibial surface.

After the tibial cut is made, the smart ligament balancer must be positioned within the knee. The surgeon must send a command signal in order to expand the balancer with a predetermined tension on both medial and lateral sides until both mobile plates are in full contact with distal femoral condyles and the predetermined tension of collateral ligaments is sensed by the force transducers embedded within the upper plates. If the medial and lateral gaps are not equal, a ligament release needs to be carried out in order to rectify the mediolateral imbalance until the flexion and extension spaces seem to be symmetric and the collateral ligaments are once again well-balanced (Fig. 3).

The relationship between the force measured on the upper surface of mobile plate and the force exerted by the actuator to expand or collapse the scissor mechanism and consequently the balancer is given by the following equation:

$$F_{Actuator} = \frac{F_{Condyle} + W + \left(\frac{W_{Arm}}{2}\right)}{Tan(\theta)} \qquad (1)$$

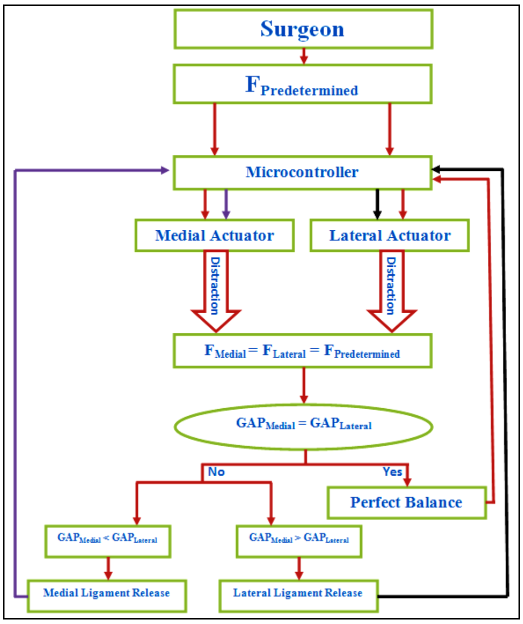

Figure 3: A schematic diagram of ligament balancing procedure using the smart knee balancer.

Where $F_{Actuator}$ is the force provided by the actuator arm, $F_{Condyle}$ is the force applied to the upper plate by the corresponding femoral condyle, W is the weight of the mobile plate and W_{Arm} is the combined weight of the two scissor arms (Fig. 4). The collapsed height of the smart ligament balancer is 5 mm while the expanded height is given by the next equation:

$$H_{Expanded} = H_{Collapsed} + 2 \cdot L \cdot \sin\theta \qquad (2)$$

Where $H_{Expanded}$ is the expanded height of the balancer, $H_{Collapsed}$ is the collapsed height of the balancer, L is the length of scissor arm and θ is the angle between the horizontal and scissor arm.

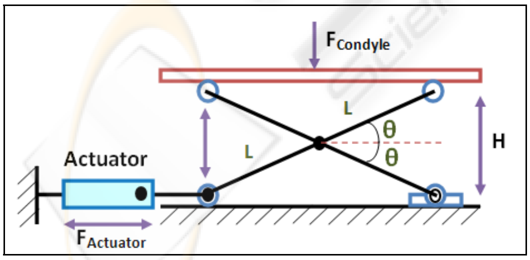

Figure 4: Scissor lift jack.

The starting angle is equal to 0° to allow the balancer to be completely collapsed with initial height of 5 mm (Fig. 5) and the ending angle must not exceed 30° in order to maintain the parallelism of the upper plates and to ensure their stability in the transversal plane. Since the length of the scissor arm equals 25 mm. Consequently and according to the equation (2), the balancer can expanded from 0 mm to 25 mm in a continuous movement.

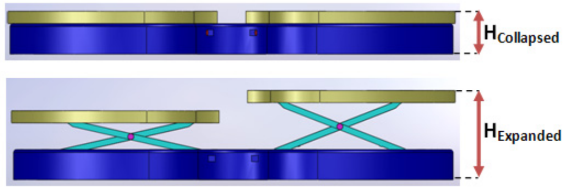

Figure 5: The collapsed height of the balancer ($H_{Collapsed}$= 5 mm) and the expanded height ($H_{Expanded}$= 30 mm).

3 CONCLUSIONS

Tibiofemoral mechanical malalignment and collateral ligament imbalance can result in a postoperative instability of the prosthetic knee which is a major complication after total knee arthroplasty (Fehring, 1994). Since surgeons strive for perfection in ligament balance, an accurate ligament balancer (Fig. 6) is indispensable to prevent postoperative complications such as instability. The importance of postoperative assessment of ligament imbalance is due to the fact that the mediolateral laxity of prosthetic knee can change and increase after total knee arthroplasty without resulting in postoperative tibiofemoral mechanical malalignment but increasing coronal ligament imbalance and consequently knee instability. The primary cause of postoperative ligament imbalance is that the intraoperative ligamentous balance couldn't be perfectly achieved at the time of surgery, even with considerable release of one of the two collateral ligaments. This might be due to the absence of adequate assessment of ligament balance during surgery. Furthermore, the mediolateral ligament balance varies postoperatively even if proper balance is performed intraoperatively.

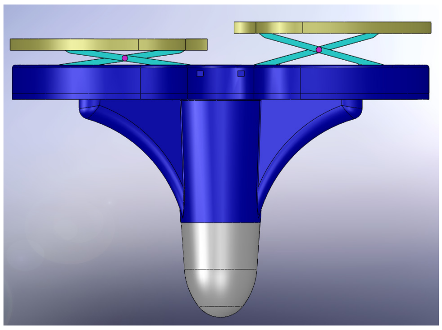

Figure 6: In vivo ligament balancer embedded onto the tibial component of knee prosthesis.

To the best of our knowledge, the smart ligament balancer proposed in this study is the first one that could quantitatively assess the mediolateral balance of collateral ligament intra- and postoperatively in both extension and flexion. In addition, this balancer could allow a continuous assessment of ligament imbalance over the whole range of flexion while most balancing instruments assess this balance at full extension and 90° of flexion and don't allow measurements at other positions of flexion (Attfield, 1996).

Since the medial and lateral collateral ligaments of knee are of different cross-section, length and shape and do not represent extensile strings, but viscoelastic, extendible structures, the ligament imbalance could not be constant at different separation gaps and depends on the compressive tension used to distract the bones. Therefore, ligament imbalance must be quantified at different distraction gaps by tensing the knee by equal forces both medially and laterally but with different force at each time. This is completely possible by means of our smart knee balancer given that the ligament imbalance is quantified by measuring the difference in height between the medial and lateral sides of a trapezoidal tibiofemoral gap produced when identical tensions are applied to both medial and lateral ligaments of the knee. In addition, the parallelism of the upper trays is perfectly ensured by the use of scissor mechanism instead of inflatable rubber bladders (Marmignon, 2004). Furthermore, the continuous movement of the upper tray ensures a continuous augmentation of the gap height rather than the discrete movement achieved by inserting spacer blocks (Crottet, 2005), which decreases the time and complexity of knee surgery.

REFERENCES

Attfield, S. F., Warren-Forward, M., Wilton, T., Sambatakakis, A., 1994. Measurement of soft tissue imbalance in total knee arthroplasty using electronic instrumentation, *Medical Engineering and Physics*, 16(6):501–505.

Attfield, S. F., Wilton, T. J., Pratt, D. J., Sambatakakis A., 1996. Soft tissue balance and recovery of proprioception after total knee replacement, *Bone and Joint Surgery*, 78(4):540–545.

Crottet, D., Maeder, T., Fritschy, D., Bleuler, H., Nolte, L.P., Pappas, I.P., 2005. Development of a force amplitude- and location-sensing device designed to improve the ligament balancing procedure in TKA, *IEEE Transactions on Biomedical Engineering*, 52(9):1609–1611.

Fehring, T. K., Valadie, A. L., 1994. Knee instability after total knee arthroplasty, *Clinical Orthopaedics and Related Research*, 299:157–162.

Griffin, F., Insall, J., Scuderi, G., 2000. Accuracy of soft tissue balancing in total knee arthroplasty, *Arthroplasty*, 15(8):970–973.

Insall, J.N., 1984. *Surgery of the Knee*, Chapter: Total knee replacement, Churchill Livingstone, 1st edition.

Insall, J.N., 1993. *Surgery of the Knee*, Chapter: Surgical techniques and instrumentation in total knee arthroplasty, Churchill Livingstone. 2nd edition.

Laskin, R.S., Riegèr, M.A., 1989. The surgical technique for performing a total knee replacement arthroplasty, *The Orthopedic Clinics of North America*, 20(1):31–48.

Marmignon, C., Leimnei, C., Cinquin, P., 2004. Robotized distraction device for knee replacement surgery, *Computer Assisted Radiology and Surgery*, 1268:638–643.