Hinged External Fixators for Knee Rehabilitation
Kinematic Concept of a Two Degree-of-Freedom System

Gianluca Gatti[1], Shadi Shweiki[1], Giorgia Lupinacci[1], Gionata Fragomeni[2] and Guido Danieli[1]
[1]*Dept. of Mechanical, Energy and Management Engineering, University of Calabria, V. Bucci, 87036 Rende (CS), Italy*
[2]*Dept. of Medical and Surgical Sciences, University of Magna Graecia, V. Europa, 88100 Catanzaro (CZ), Italy*

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Abstract: Hinged external fixators are used in knee dislocation treatment, where they have shown their effectiveness. They are proposed as a technique to protect ligament reconstructions while allowing early postoperative rehabilitation. A hinged external fixator usually consists of two rigid links connected to each other by a revolute joint. Each link is then fixed to the femur and tibia, via direct pin fixation. A single-axis hinged external fixator thus well accommodates the main knee movement, i.e. the flexion and extension. This paper presents an investigation on the conceptual idea of a double-axis hinged external fixator for the human knee, which accommodates for both flexion-extension and longitudinal internal-external rotation of the tibia respect to the femur. The potential advantage of such a design is foreseen in the increasing range of motion in postoperative knee rehabilitation and a better accommodation of natural knee motion.

1 INTRODUCTION

Injuries and trauma that may occur in the human knee often lead to difficulties in having a fast and complete rehabilitation. Among these trauma, dislocation is one of the most severe injuries. Clinical outcomes after knee dislocations are frequently unsatisfactory, and pain, instability and arthrofibrosis are the most frequent complications (Stannard et al., 2003; Stayner and Coen, 2000). The instability basically lies in the injury of ligaments, and in some cases, even after repair, there is insufficient stability for early rehabilitation. This is the reason why preliminary reports on such treatment focused on achieving stability of the ligaments by means prolonged immobilisation during the postoperative period, although this would lead to stiffness of the joint (Noyes and Barber-Westin, 1997; Shapiro and Freedman, 1995).

In more recent studies, authors intensely advocate early and aggressive mobility despite the risk of ligament repair or reconstruction failing (Cole and Harner, 1999; Yeh et al., 1999), and this led to the concept of the fixator with motion capabilities (Deszczynski et al., 2000; Fitzpatrick et al., 2005). A hinged external fixator usually consists of two rigid links connected to each other by a revolute joint. Each link is fixed to the femur and tibia through direct pin fixation. Previous biomechanical studies showed that a single-axis hinged external fixator is able to reproduce and accommodate the normal knee kinematics in a limited portion of the range of motion without harmfully loading the structures (Sommers et al., 2004; Wroble et al., 1997). Such external hinge, set to an approximate rotational axis of the articular joint, neutralises the displacing forces during the movement, and control the natural repair mechanism of the ligament apparatus. The fixator will thus allow patient mobility without the risk of loading the injured area during treatment and rehabilitation.

The main difficulty in the application of hinged external fixators is the implantation and, in particular, the location of the articular joint axis of rotation. Commonly, this axis is manually identified by means of radiographs on the base of bony landmarks (Fragomeni et al., 2006; Richter and Lobenhoffer, 1998) and then the mechanical hinge of the fixator is aligned through screw adjustments. This technique may be prone to errors and the approximation in enforcing an articular joint to an unnatural mechanical behaviour may lead to unwanted outcomes in post-traumatic knee kinematics. This latter is, in fact, a result of a

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complex interaction of bones, ligaments and muscles, which may be completely described by six degrees of motion during dynamic activities (Palastanga et al., 1989; Lafortune et al., 1992). Only as a first approximation, such kinematics may be modelled as a simple flexion-extension movement, which is indeed coupled to the longitudinal rotation of the tibia (Piazza and Cavanagh, 2000), making knee kinematics three-dimensional.

In this paper, we present the conceptual idea of a two degree-of-freedom (DOF) system from the kinematic point of view, which may cope with both the two dominant movements of the knee, i.e. the flexion-extension (FE) and the longitudinal internal-external rotation (LR). The aim of the paper is mainly to show the most relevant kinematic issues involved in such a design. As such, some of the forthcoming issues related to the materials selection, and to the specific fastening and assembling considerations are not treated in the following sections.

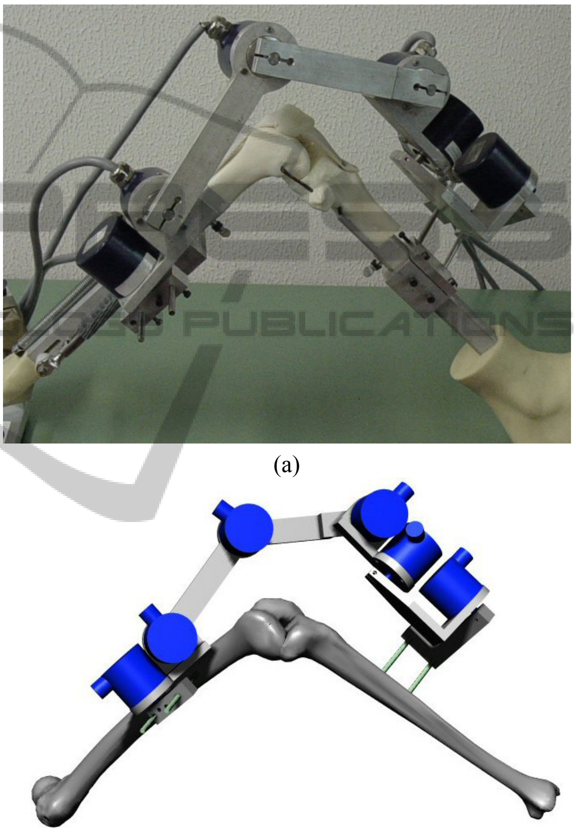
Such a device design would potentially allow for a better rehabilitation, while retaining the main advantages of articulated external fixation. And this would be due to the fact that an additional degree of mobility, respect to traditional hinged fixators, would allow the articular knee joint to better accomplish its natural movement.

2 MATERIALS & METHODS

2.1 Knee Joint Axes Identification

Design and implant of hinged external fixators requires a good understanding ok knee kinematics and accurate measurements. Among the different techniques effectively used for joints kinematics detection, relying on electromagnetic, imaging or ultrasound systems (Kinzel and Gutkowski, 1983; Bull and Amis, 1998), instrumented spatial linkages (ISLs) are perhaps some of the most commonly used 6-DOF measuring devices for anatomical joints motion description. An application of an ISL in place on a MITA Endo Leg system and on a virtual knee model is reported in Figure1(a) and (b).

An ISL consists of a series of seven rigid links connected to each other by six rotational sensors. The end segments of the ISL are attached to the two bones whose relative motion is to be measured, and this motion can be estimated by the geometry of the linkage and the transducers reading. The use of ISLs to measure three-dimensional human joints motion were effectively applied for either in vitro or in vivo studies (Lewandowski et al., 1997; Van Sint Jan et al., 2002), and also effectively used whenever direct fixation to bones is required (Gardner et al., 1996; Danieli et al., 2005a; Ishii et al., 1997), as an alternative approach to active robotic systems (Danieli et al., 2005b). Requirements for adequate measurements involve advanced calibration of the devices (Liu and Panjabi, 1996; Gatti et al., 2010; Gatti and Danieli, 2008; Sholukha et al., 2004; Gatti and Danieli, 2007).



(a)

(b)

Figure 1: An application of an ISL to measure knee kinematics of (a) a MITA Endo Leg System and (b) a virtual knee model.

Several authors (Hollister et al., 1993; Roland et al., 2010; Gatti, 2012), presented and validated techniques to estimate and identify both the functional FE axis and the LR axis of the human knee. Experimental clinical outcomes based on literature, e.g. Smith et al. (2003) and Williams and Logan (2004), may be also used as a guide to correctly identify the location of knee axes and help in correctly setting the external fixator implant.

With reference to Figure 2, for instance, the technique presented in (Gatti, 2012) let one define the FE axis by identifying the components of its unit vector $\mathbf{u_F}$ and the coordinates of a point O_F in an orthogonal reference frame (x_B,y_B,z_B) attached to the femur. In a similar way, the LR axis is defined by identifying the components of its unit vector $\mathbf{u_R}$ and the coordinates of a point O_R in an orthogonal reference frame (x_E,y_E,z_E) attached to the tibia. These geometrical features are easily identified when using an ISL with its end fixtures attached rigidly to the proximal and distal bones.

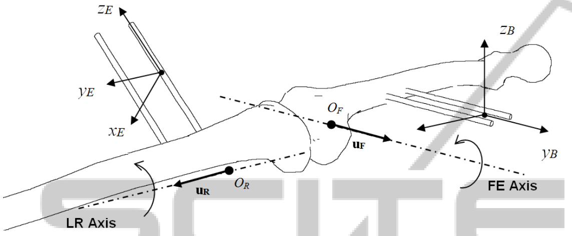


Figure 2: Identification of the dominant axes of the knee joint according to the procedure described in (Gatti, 2012).

Although these techniques appear to be applied to virtual models, and clinical applications to cadaveric knee specimens seems not to be reported yet, they seem to be potentially applicable in experimental campaigns on in-vitro fresh-frozen cadaveric specimens to clinically identify the approximate location of the two dominant axes with respect to specific bony landmarks.

2.2 External Fixator Kinematics

Once the approximate FE axis and the LR axis are identified, an articulated hinged external fixator with two degrees of freedom, i.e. having two rotational hinges, may be designed having its mechanical hinge joints aligned to the functional knee axes, in a similar manner than that currently suggested in the recommended technique and instructions by manufacturers of single-axis hinged external fixators (e.g. Compass Universal Hinge, Smith&Nephew).

In order to allow for an accurate alignment, the kinematic structure of the 2-DOF external fixator should be designed properly, such to have the capability to set the correct position and orientation of each functional axis respect to the relative bone. This can be assured by the use of a multi-DOF adjustable kinematic structure which is attached at one end to the fixation pins of the correspondent bone, and at the other end is aligned to the correspondent functional axis. The kinematic structure reported in the schematics of Figure 3, illustrates these requirements. In this figure, different mechanical joints are identified by different letters, where *R* stands for ‘rotational’ joint, which allows only a relative rotation to its joined links around its axis of rotation, and *C* stands for ‘cylindrical’ joint, which allows for simultaneous independent rotation and translation of its joined links around and along its axis of motion. As a whole, the kinematic chain reported in Figure 3, has three rotational joints each allowing for one relative DOF and two cylindrical joints, each allowing for two relative DOF – it then has a total of one DOF which is uses to adjust the kinematic structure according to the bone segment.

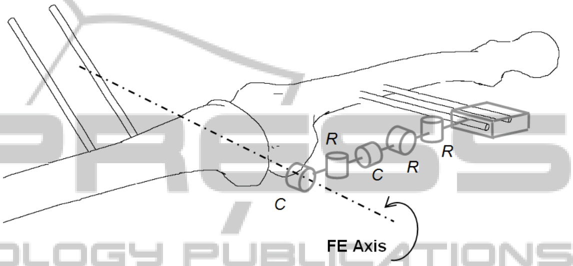


Figure 3: Schematics of the multi-DOF kinematic structure to allow for alignment of the functional FE axis. An equivalent structure is used, respect to the tibia, to allow for alignment of the functional LR axis.

Once each functional axis is identified in its correspondent reference frame, the multi-DOF structure, as sketched in Figure 3, may be used to set the correct alignment both in position and orientation.

The coupling between the two structures is then realized by designing a two DOF mechanism which allows for free independent rotations around the two functional axes of the knee joint. This is illustrated in the sketch of Figure 4.

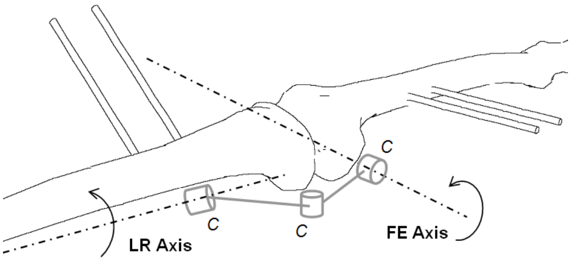
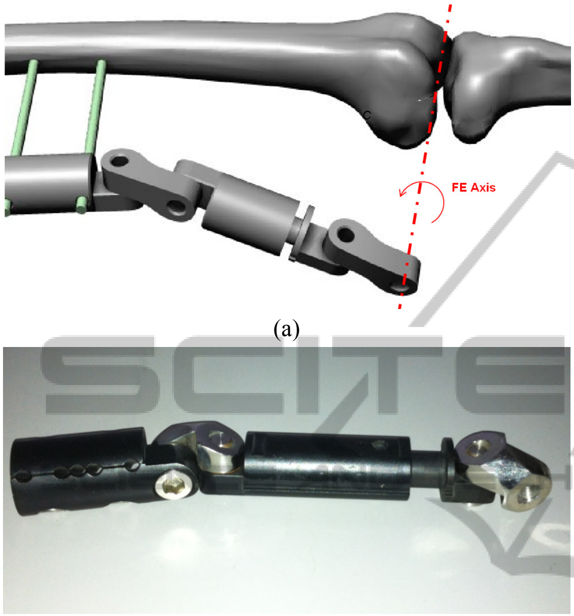


Figure 4: Schematics of the 2-DOF mechanism to allow for independent rotations around the two functional axes of the knee joint.

The mechanism is realized by assembling three cylindrical joints to assure a fixed orientation between the two functional knee joint axes.

The mechanical assembly sketched in Figure 3 may be realized by connecting standard fixator components. A virtual CAD model of the proposed multi-DOF structure is illustrated in Figure 5(a), while a photograph of the correspondent standard component assembly is shown in Figure 5(b).



(a)

(b)

Figure 5: Multi-DOF structure used to assure correct position and orientation of functional joint axis respect to the correspondent bone: (a) virtual CAD model and (b) photograph of an assembly using standard fixator components.

From the mechanical point of view, the 2-DOF mechanism sketched in Figure 4 presents an issue related to the fact that it is not possible to align a mechanical joint to the LR axis since it is located internally to the shank. This is overcome by designing an equivalent mechanism, whose virtual CAD model is shown in Figure 6. In this assembly the DOF associated to the FE rotation is realized by the use of a hinge joint located externally to the knee, while the DOF associated to the LR rotation is realized by the use of a circular ring coupled to a mating feature which realizes an equivalent rotational motion without the need of physically locating a mechanical hinge on the LR axis. The full virtual assembly of the external fixator, with the multi-DOF structures connected to the 2-DOF mechanism is illustrated in Figure 7.

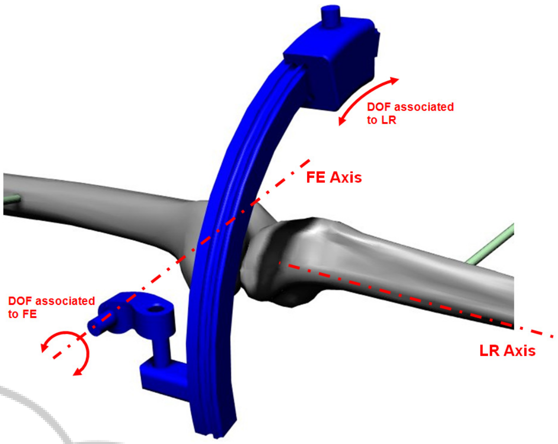
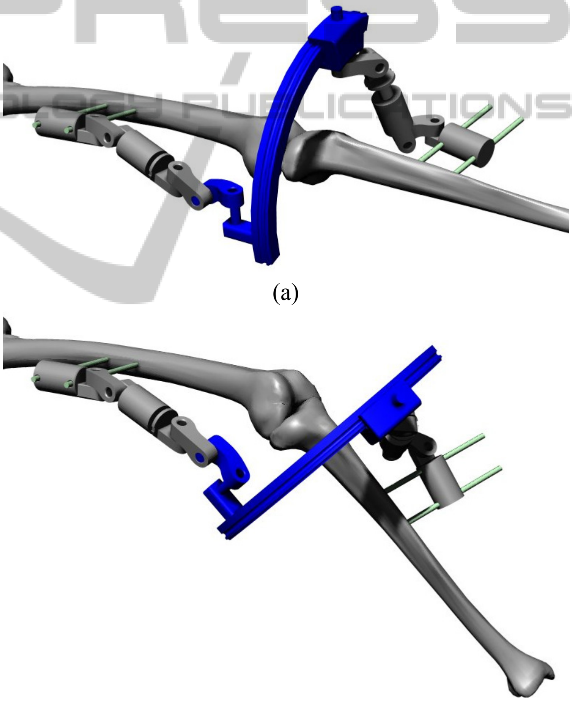


Figure 6: Virtual CAD model of the 2-DOF mechanism used to assure free independent rotations around the two functional axis of the knee joint.



(a)

(b)

Figure 7: Virtual CAD model of the whole 2-DOF hinged external fixator implanted to a virtual knee model: (a) assembly in the full extended configuration with no LR rotation, and (b) assembly in a configuration such that the angle of flexion is about 45° relative to the configuration in (a), and the angle of longitudinal rotation is approximately 5° relative to the configuration in (a).

The 2-DOF hinged external fixator is then designed so that it may be correctly implanted once the relative location and orientation of the two functional knee joint axes are identified by the use of an ISL. The fixation pins on each bone segment assure that both the ISL and the external fixator have a unique reference frame association, so that errors may be reduced at source. The multi-DOF structures are cinematically designed so has to allow for a proper degree of mobility in order to set the clamping fixture on the fixation pins according to the specific thigh/shank conformation. Once each multi-DOF structure is adjusted to correctly match the correspondent functional axis, each joint of the structure is locked using the screw connections adopted in standard fixators, as shown in Figure 5(b). This assures that the relative position and orientation of the functional axes remain constant throughout the knee joint motion.

Simulations are finally performed on a virtual model of the knee as illustrated in Figure 7, assuming fixed axis of FE and fixed axis of LR. To account for a more general case, the functional axes are chosen neither to be orthogonal nor to intersect each other. More specifically, a simulation is run by assuming, with reference to Figure 2, the following location for the functional FE axis ${}^{B}O_F = (190, 80, -10)$ mm, ${}^{B}\mathbf{u}_\mathbf{F} = (0.1219, 0.9775, 0.1724)$ and the following location for the functional LR axis ${}^{E}O_F = (16.068, -107.57, 139.52)$ mm, ${}^{E}\mathbf{u}_\mathbf{F} = (0.0733, 0.9779, 0.1956)$, where the superscript on the left-hand side denotes the frame of reference respect to which coordinates are given. The angle of flexion and longitudinal rotation are varied according to the plot in Figure 8. The simulations performed confirmed the validity of the kinematic solution proposed in the paper.

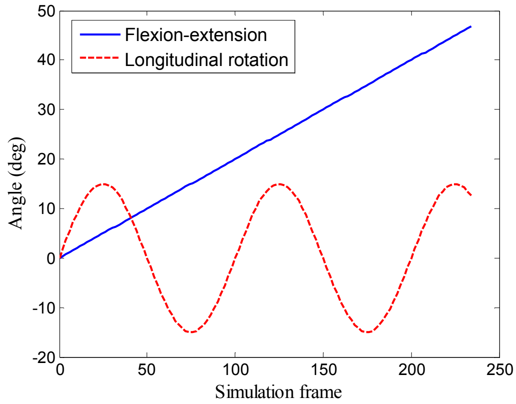


Figure 8: Angles of flexion-extension and longitudinal rotation imposed in simulation.

3 CONCLUSIONS

The conceptual idea of a double-axis hinged articulated external fixator with two degrees of freedom is illustrated in this paper. Such a system is based on clinical findings which shows that, in the human knee motion, the flexion extension movement is coupled with a longitudinal internal-external rotation of the tibia. In knee dislocations treatments, where aggressive mobility and rehabilitation is advocated, such a biomechanical devices could potentially improve the motion capabilities currently provided by available single-axis external fixators, and hopefully improve postoperative outcomes for patients. The current work limited the presentation to the kinematic design and conceptualization of the fixator. As such, the mobility of the device, its degree of adjustment according to patient, and its main kinematic issues have been addressed. Kinematic simulations have been performed to assess the validity of the design. The main fixator components are those used in other standard fixators, so that the design of specific features is only limited to the innovative parts achieving the double-axis movement. Comparative analyses with other fixators is foreseen, and extensions of the present work will include also an insight into the manufacturing issues, strength requirements and material selection. A preliminary prototype of the proposed external fixator is planned to be realized and applied to a physical model of the knee joint available in laboratory, once its functional axes have been estimated by the use of the available ISL using the procedures described in the literature.

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