Hinged External Fixation of the Knee

Intrinsic Factors Influencing Passive Joint Motion

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Objective: To measure changes in knee kinematics after the application of articulated external fixators along a previously described knee flexion/extension axis and 16 specific "off-axis" fixator hinge configurations.

Design: Cadaver, biomechanical study.

Setting: Biomechanics laboratory.

Participants: Nine fresh cadaver knee specimens.

Intervention: Each specimen was mounted on a custom-built frame that constrained the knee to move about a fixed flexion/extension axis. Passive knee motion was induced, and the resulting flexion moment was measured. Data were collected for the on-axis fixator position and 16 distinct rotational and translational off-axis positions. In addition, effects of tibial translation and rotation were investigated.

Main Outcome: Range of motion (ROM) attainable within a moment envelope of ±1 N-m and average energy required to impart movement.

Results: The average ROM for unconstrained knees was 122°. Constraining the knee to rotation around an on-axis aligned hinge significantly reduced the ROM by 35% to 79°. The 5-mm posterior translated hinge was the only alignment to show on average a slightly larger ROM (86°) than the on-axis hinge. All other hinge alignments showed decreased average ROM compared with the on-axis position. Tibiofemoral alignments significantly affected the obtainable ROM for the on-axis aligned hinge.

Conclusion: It was not possible to replicate precisely the complex kinematics of the knee using a single axis fixator over the entire ROM. Using the axis of rotation previously defined in the literature, however, it was possible to obtain a limited ROM of the knee without placing excessive forces on the periarticular structures.

Key Words: knee, external fixation, rotation axis, hinge, range of motion

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Rigid spanning external fixation is becoming increasingly popular for severe tibial plateau fractures, supracondylar femur fractures, and knee dislocations as a bridge to internal fixation and as a definitive treatment modality.[1–3] Rigid immobilization of joints after injury may have deleterious effects on articular cartilage and soft tissues.[4–6] Reports of articulated external fixation of the knee are sparse[7–10]; however, multiple studies have advocated this treatment method for severe injuries at other joints.[11–14] Success with articulated external fixation at the ankle and elbow led us to investigate the feasibility of applying this technology to the knee.[11,12,15,16]

The complexity of knee kinematics makes articulated external fixation at this joint difficult. More recent studies have relied on advanced mathematical techniques to describe knee kinematics.[17–21] Some studies have suggested, however, that knee motion occurs as a composite motion that may be resolved into more simple rotations about two axes.[22–26] These studies showed that knee flexion and extension occur about a single, fixed axis that is oblique to the familiar anatomic planes and nearly parallel to the transepicondylar axis.[22] The knee also undergoes internal and external rotation about a second axis located in the medial compartment.[24,25,27] These axes are linked, and the knee must move about both axes simultaneously to reproduce normal kinematics.[27] Anterior-posterior translation (rollback) occurs in the normal knee between 15° and 90° of flexion. The magnitude of rollback was measured by Todo et al[28] to be in the range of 2 mm. These investigators considered this amount of anterior-posterior motion to have a "negligible" effect on knee kinematics.

These data suggest that it may be possible to align a simple hinged external fixator along the knee flexion/extension axis and obtain limited, but physiologic motion without placing high stresses on the surrounding structures. To our knowledge, no previous study has shown quantitatively how such a fixator could be applied and what its effect would be on knee motion. The present study quantified for the first time intrinsic effects of fixator application on passive knee motion, disregarding extrinsic effects, such as muscular impingement on the fixator pins. We hypothesized that application of an articulated, single hinge external fixator along the previously described knee flexion/extension axis would allow the largest knee range of motion (ROM) with the least resistance to motion when compared with 16 specific "off-axis" fixator hinge configurations.

MATERIALS AND METHODS

Nine fresh cadaver specimens obtained from donors with an average age of 69 ± 10 years were inspected clinically and radiographically to ensure they were free of osteoarthritis or pathologic laxity. They were prepared by removing all superficial soft tissues, while carefully preserving the joint capsule, ligaments, and extensor mechanism. The femur and tibia were amputated 13 cm from the joint line and potted in PMMA cylinders.

The knees were placed in a custom-designed bilateral articulated external fixator that constrained the knee to move about a single axis (Fig. 1). The fixator axis initially was aligned under fluoroscopic guidance to coincide with the knee flexion/extension axis using a previously described technique[29] that relies on the radiographic landmarks defined by Hollister et al[24] and Elias et al.[23] This fixator configuration was termed the *on-axis* position. The experimental apparatus allowed the fixator axis to be aligned in 16 additional positions not coincident with the predefined flexion/extension axis of the knee. These axis positions were termed *off-axis* fixator configurations (Fig. 2).

If the external fixator axis and the knee rotation axis are not coincident, the knee and the fixator "bind," and high forces can develop in the periarticular structures. This binding can be detected by an increase in the force required to move the knee through its ROM. To ensure that binding did not produce irreversible damage to specimens, the rotational torque required to impart motion to the knee was not allowed to exceed 1 N-m. This defined a "safe" envelope of motion in which forces on the knee were not excessive.

The specimen and fixator were placed in a material test system (Instron 8874; Canton, MA), and a passive motion cycle was simulated. For each test cycle, the knee was moved at a constant angular velocity of 9°/sec from the neutral position into extension until the rotational torque limit of 1 N-m was reached. The knee was returned to the neutral position, then moved into flexion until the torque limit was reached. Neutral position was defined as 60° of flexion (half of a −5° to 125° motion cycle).

Data were collected for the unconstrained knee (no fixator), the on-axis position, and each of the 16 off-axis configurations. The 16 off-axis configurations included 8 translational changes and 8 rotational changes in the fixator axis (Fig. 2). Data collection during the motion cycle included the flexion angle and the rotational torque needed to impart motion. The end points of motion defining the 1 N-m motion envelope also were recorded. All torque and flexion angle data were recorded simultaneously at a sampling rate of 50 Hz (six samples per degree of flexion) using a data acquisition system (SCXI 1120; National Instruments, Austin, TX).

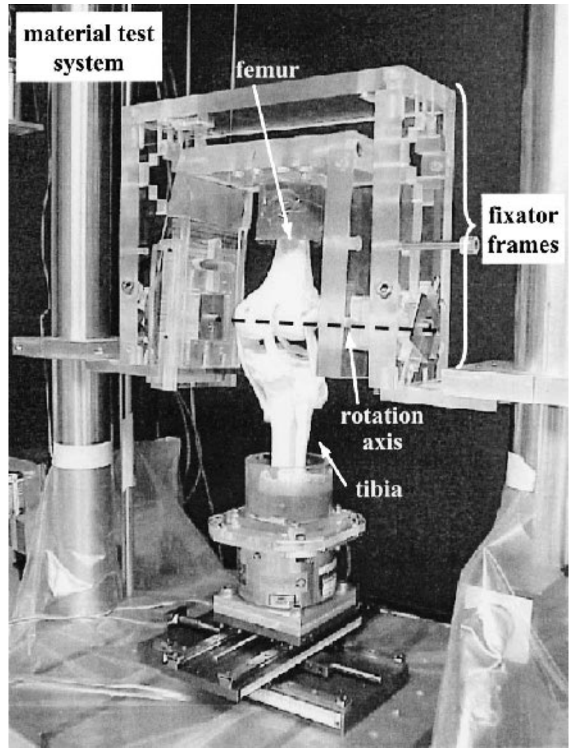


FIGURE 1. Knee motion apparatus mounted on material test system, shown for clarity with a synthetic knee. The knee was constrained to move about the axis of a rigid, bilateral external fixator construct. The tibia was fixed to the testing machine and the outer frame of the fixator. The femur was mounted to the inner frame of the fixator.

Knee motion after application of an external fixator also may be affected by translational and rotational malalignments of the tibia with respect to the femur. To investigate fully the effect of these malalignments, an additional set of experiments was performed. With the fixator in the on-axis position and the knee flexed to 60°, the tibia was allowed to rest in its neutral position. Subsequently the knee was taken through a ROM as previously described. The tibia was moved to one of eight translational and four rotational malalignment configurations (Fig. 3). ROM and corresponding torque data were recorded for each tibial position. To ensure the reproducibility of data over the test series, repeat measurements of the on-axis configuration were performed at the beginning, in the middle (between off-axis and tibial alignment tests), and at the end of the test series for each specimen.

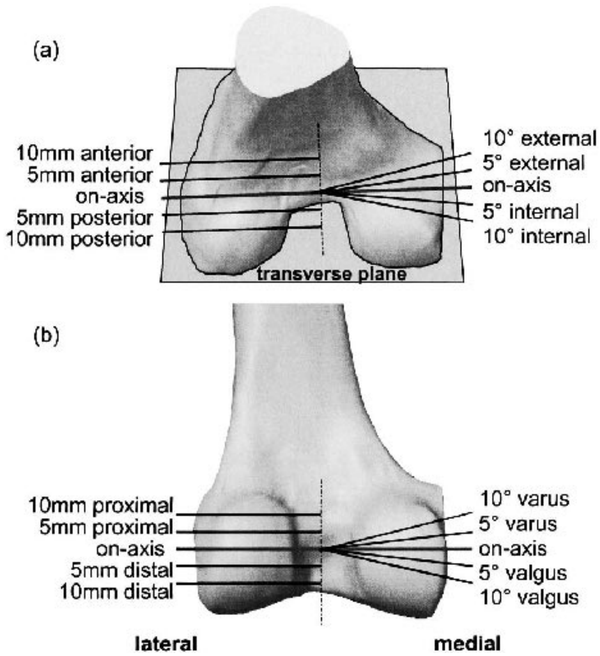


FIGURE 2. On-axis and 16 off-axis hinge configurations in transverse (A) and coronal (B) plane projection.

Data analysis consisted of calculating the average ROM within the 1 N-m moment envelope for the unconstrained knee and for each of the fixator axis configurations. The energy required for knee flexion was derived by calculating the area under the flexion angle versus moment curves. Dividing this number by the total ROM gave a representation of the average amount of energy required to move the knee through each degree of flexion. This calculated energy value served as a summary index for the resistance to movement over the ROM and allowed direct comparison of the effect of different fixator axis configurations on knee motion. Statistical analysis comparing the unconstrained, on-axis, and off-axis data sets was performed using a two-tailed, paired Student *t* test with a 95% confidence interval.

RESULTS

Repeat measurements of the on-axis fixator configuration revealed consistent results over the course of each test series and ensured absence of specimen degeneration or testing-induced damage.

Fixator Axis Configuration

The average ROM for the unconstrained knee was 122° (Fig. 4). When constrained to rotate about the on-axis fixator position, the ROM decreased to 79°. This represented a 35% decrease in the ROM and was statistically significant ($P < 0.05$). Only one off-axis fixator configuration showed a larger ROM than the on-axis position. The 5-mm posterior axis translation had an average ROM of 86°; however, this was not significantly different ($P = 0.4$) from the on-axis ROM. The 10-mm posterior translation, 5° internal rotation, and 5° varus rotation showed a decreased ROM that was not statistically different from the on-axis position ($P = 0.27$, 0.10, and 0.70). All other off-axis configurations showed significant ($P < 0.05$) decreases in ROM relative to the on-axis position, with the 10-mm anterior axis translation resulting in the smallest ROM of 21°.

The unconstrained knee achieved an average of 3° of hyperextension. Application of the external fixator decreased knee extension in all cases. The greatest extension within the 1 N-m envelope was achieved with the on-axis position, yielding an average of 19° short of full extension. The 5-mm posterior translation, 5-mm proximal translation, 5° external rotation, and 5° varus rotation showed slight, but not statistically significant decreases in extension relative to the on-axis position ($P = 0.80$, 0.15, 0.08, 0.53). The remaining fixator axis configurations showed significant reductions in extension.

The unconstrained knee showed an average of 119° of flexion within the total 122° ROM. The on-axis fixator position decreased the average maximum knee flexion to 98°. The 5-mm and 10-mm posterior fixator axis translations resulted in significantly better knee flexion than the on-axis position (106° and 107°). The 5° and 10° internal rotation and the 5° varus rotation showed no significant differences in maximum flexion. The remainder of the off-axis configurations resulted in significantly less maximum flexion than the on-axis fixator position.

The energy required to move the unconstrained knee through its ROM was 43 mJ/° (Fig. 5). The on-axis fixator position significantly increased the required energy to 351 mJ/°. The 5-mm (207 mJ/°) and the 10-mm (136 mJ/°) posterior translations of the fixator axis showed significantly lower required energy than the on-axis position. The 5° and 10° in-

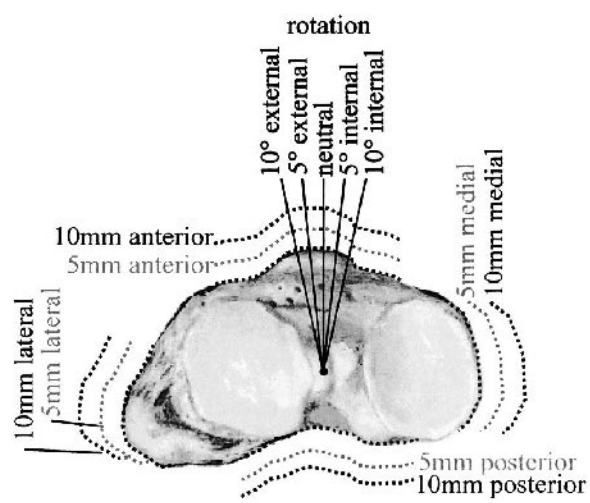
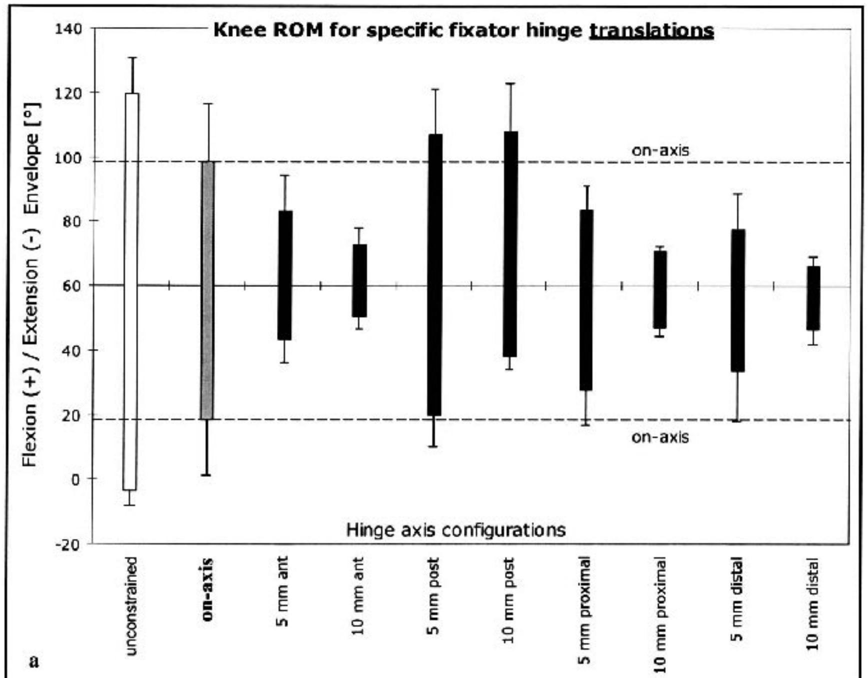
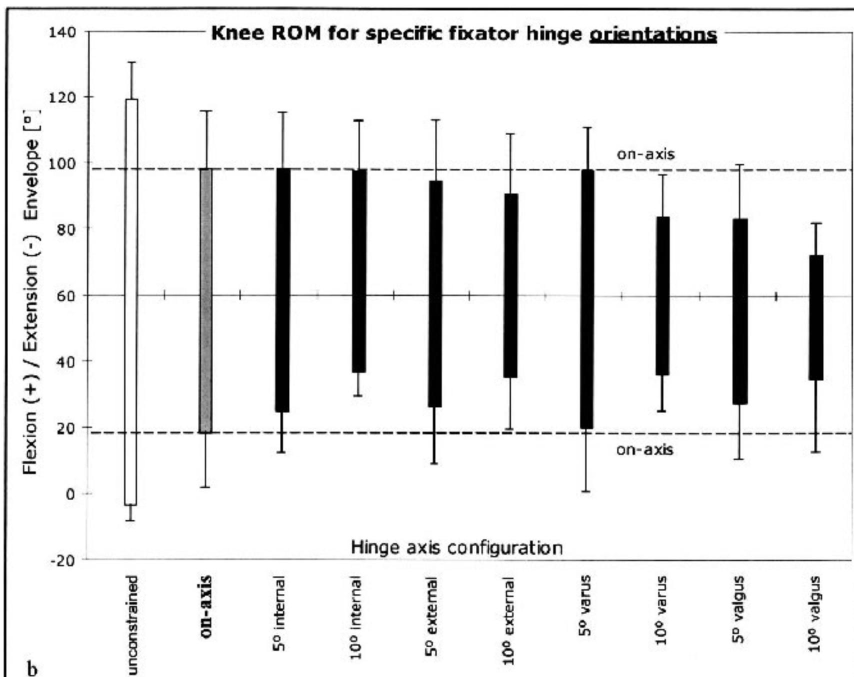


FIGURE 3. Tibial alignment: neutral position, eight translational and four rotational malalignments.



Significance	unconstrained	on-axis	5 mm ant	10 mm ant	5 mm post	10 mm post	5 mm proximal	10 mm proximal	5 mm distal	10 mm distal
ROM	*	Reference	*	*			*	*	*	*
Extension	*		*	*		*		*	*	*
Flexion	*		*	*	*	*	*	*	*	*



Significance	unconstrained	on-axis	5° internal	10° internal	5° external	10° external	5° varus	10° varus	5° valgus	10° valgus
ROM	*	Reference		*	*	*		*	*	*
Extension	*		*	*		*		*	*	*
Flexion	*				*	*		*	*	*

FIGURE 4. Effects of fixator axis configurations on knee ROM. A, Fixator off-axis translations. B, Fixator off-axis rotations. Statistically significant changes ($P < 0.05$) in ROM compared with the on-axis fixator position are indicated in tabular form by an asterisk.

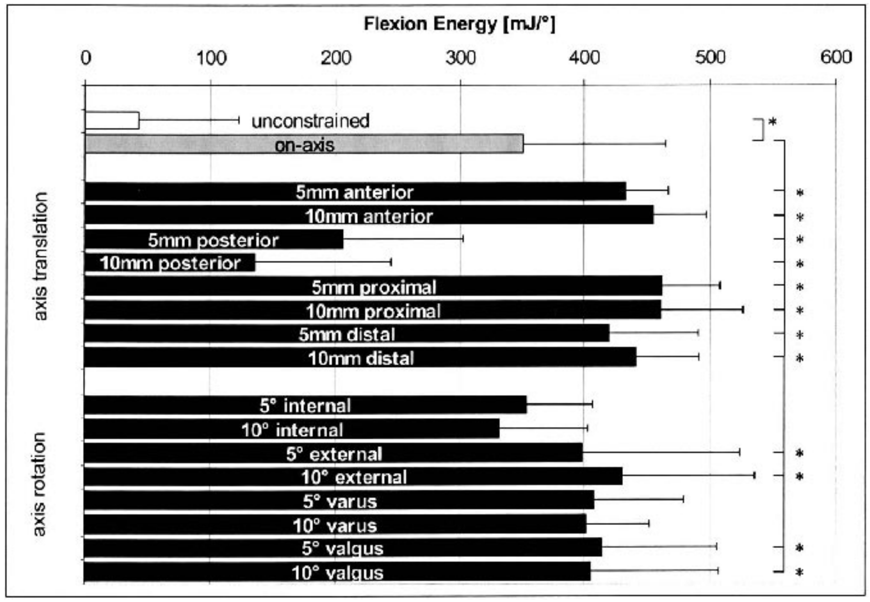


FIGURE 5. Average knee flexion energy required for specific axis configurations. Smaller bars reflect easier knee motion. Statistically significant changes ($P < 0.05$) in ROM compared with the on-axis fixator position are indicated by an asterisk.

ternal rotations and the 5° and 10° varus rotations were not significantly different from the on-axis position. All remaining off-axis configurations showed significant increases in the energy required to move the knee through its ROM relative to the on-axis position. Flexion angle versus torque plots show that when the torque began to increase, it increased rapidly for most of the off-axis configurations (Fig. 6).

Tibial Alignment

Anterior translation of the tibia from the neutral position of 5 mm and 10 mm significantly increased the amount of flexion to 103° and 108° (Fig. 7). Anterior translation also significantly decreased the amount of extension to 30° for the 5-mm translation and 47° for the 10-mm translation. Posterior translations of 5 mm and 10 mm significantly decreased the average flexion to 86° and 72°. Extension was significantly increased to 15° and 16° for the 5-mm and the 10-mm posterior translations. Medial translations of 5 mm and 10 mm decreased flexion to 93° ($P = 0.01$) and 88° ($P < 0.05$). Extension also was significantly decreased to 25° and 35° after medial tibial translation of 5 mm and 10 mm. Lateral tibial translation did not significantly affect extension.

Internal tibial rotation of 10° significantly decreased maximum extension to 32° but had no effect on the amount of flexion obtained. The 5° and the 10° external tibial rotations significantly increased the amount of extension obtained to 11° and 11°. The 10° external rotation significantly decreased the amount of flexion to 92°.

DISCUSSION

To our knowledge, only one previous study has evaluated knee kinematics after placement of an articulated external fixator. Simonian et al[8,9] aligned a simple hinge with the knee axis defined by a line connecting the isometric origins of the medial and lateral collateral ligaments. They noted a trend toward increasing joint compression and posterior translation as

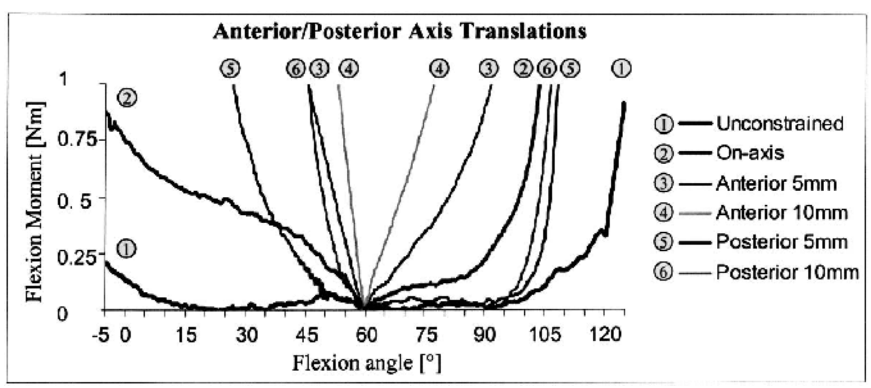
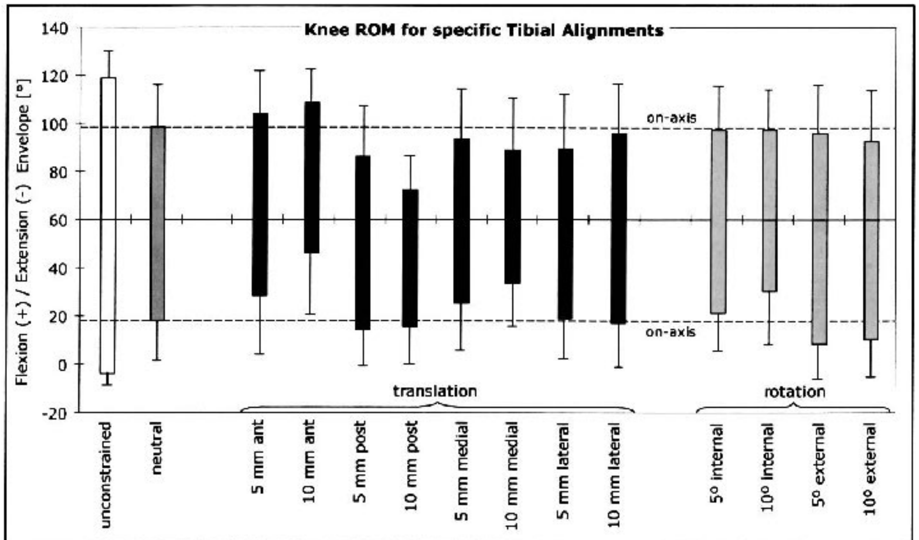


FIGURE 6. Representative flexion moment recording of one specimen during knee flexion and extension.



Significance	unconstrained	neutral		5 mm ant	10 mm ant	5 mm post	10 mm post	5 mm medial	10 mm medial	5 mm lateral	10 mm lateral		5° internal	10° internal	5° external	10° external
ROM	*	Reference			*	*	*	*	*	*				*	*	
Extension	*			*	*	*	*	*	*					*	*	*
Flexion	*			*	*	*	*		*	*						*

FIGURE 7. Effects of tibial alignment on knee motion. Eight tibial translations (center) and four tibial rotations (right) are depicted compared with the unconstrained tibia and the neutral tibial alignment. Statistically significant changes ($P < 0.05$) in ROM compared with the "neutral" fixator configuration are indicated in tabular form by an asterisk.

the knee moved toward flexion. These findings were most prevalent after sectioning the knee ligaments, suggesting that ligamentous constraints played an important role in defining knee kinematics despite the presence of a hinged fixator. No off-axis measurements were performed, and the forces on the ligaments were not measured.

The present study is unique in its attempt to evaluate knee motion within a "safe force window" using a previously described axis of rotation and several specific deviations from that axis position. Only the flexion/extension axis was used for fixator alignment; no attempt was made to reproduce the internal/external rotation axis. Simply constraining the knee to move about a single flexion/extension axis decreased its ROM by 35%, with even greater decreases in motion for almost all off-axis configurations. The 5-mm and the 10-mm posterior fixator axis translations outperformed the on-axis position in several parameters. Both posterior axis translations showed greater flexion and lower energy per degree of flexion than the on-axis position. The 5-mm posterior translation also showed better overall ROM and no difference in extension relative to the on-axis position. This indicates that optimal knee motion is not bound to one specific axis position. Rather the inherent laxity of knee ligaments allows the fixator axis to be reasonably coincident with the knee rotation axis within a range of at least 5 mm posteriorly, starting with the on-axis position. It is likely that inherent laxity of the knee ligaments allows for some flexibility in the axis position, specifically in posterior direction.

If the knee and fixator axes are not coincident, aberrant forces are placed on the ligaments and articular surfaces as they resist the abnormal motion imposed by the fixator hinge. The inherent laxity in the knee relative to more constrained joints, such as the ankle and elbow, should allow a limited ROM without binding, even if the axes of rotation are not coincident. This differs from the elbow, where there is little ligamentous laxity, and the fixator must be aligned precisely with the axis of rotation.[12] When the end points of this laxity are reached, however, the knee and the fixator begin to bind, and the forces increase dramatically. This was evident in the present study: The knee initially moved through its ROM without difficulty, but when the torque began to rise, it did so quickly until the 1 N-m end point was reached. Excessive stresses caused by binding may predispose the knee to late instability by failure of ligament reconstructions or in healing of ligaments in an elongated fashion. Increased stresses on articular surfaces also may be deleterious to chondral and fracture healing.

The previous descriptions of knee kinematics found that the flexion/extension axis was most important for the mid-ROM and that the internal/external rotation axis became important for reproducing motion at the extremes of knee flexion and extension.[23–26,30] If the fixator allows flexion and extension only about a single axis, but knee kinematics require internal/external rotation about a second axis, the knee eventually will bind, and the forces will increase. This is independent of the accuracy of flexion/extension axis alignment and explains the higher input torque requirements observed in the extremes of flexion and extension.

The position of the tibia at the time of fixation also plays a role in the amount of knee motion obtained after fixator application. Anterior and posterior translations of the tibia before application of the hinge decreased knee motion, likely because of preloading the cruciate ligaments. The knee ligaments appear to play a significant role in defining knee motion, and preloading these ligaments likely leads to altered knee kinematics and earlier binding. Similar alterations in motion were seen for internal and external rotation of the tibia. It seems vital that the fixator be applied with the tibia in neutral position because aberrations of 5° or 5 mm can significantly affect overall knee motion.

Limitations of this study include the use of the 1 N-m torque limit for the safe ROM; this may be low relative to the forces seen in the knee during clinical rehabilitation of severe periarticular knee injuries. A 1 N-m torque is equivalent to the torque on the shoulder when holding a 0.1-kg weight at arm's length. It is likely that in clinical use the knee experiences torques in excess of this limit, and the patient achieves a greater ROM. We chose this low limit as a best-case scenario in which the forces would be well below those that would be detrimental to soft tissue or bony healing. If one closely inspects the flexion versus torque plots, however, it is evident from the slopes of the curves that the trends noticed in this study should be applicable at higher loading levels (Fig. 6). Additionally the fixator used in this study was much more rigid than a typical hinged fixator used in clinical settings. A less rigid hinge allows some elastic deformation and conceivably could allow a greater ROM before binding occurs.

This study has shown that knee motion after articulated external fixation allows a limited, but physiologic ROM. The study results are limited, however, to intrinsic factors constraining knee motion, such as geometric constraints and periarticular ligamentous structures. The study did not evaluate limitations caused by extrinsic factors, such as quadriceps muscle impingement on the femoral pins. In the clinical scenario, these extrinsic factors could contribute further to knee motion resistance.

CONCLUSION

It was not possible to replicate precisely the complex kinematics of the knee using a single axis fixator over the entire ROM. Using the axis of rotation previously defined in the literature, however, it was possible to obtain a limited ROM of the knee without placing excessive forces on the periarticular structures. With the exception of the 5-mm posterior axis translation, all the off-axis configurations greatly reduced the safe ROM, indicating that it is important to align the fixator axis accurately along the flexion/extension axis of the knee. Alignment of the tibia also plays a role in determining the envelope of safe motion. Care must be taken to align the tibia in neutral position relative to the femur to prevent aberrant periarticular forces after fixator placement.

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