INTRODUCTION

The effects of ligament deficiency on walking kinematics and cartilage degeneration have been investigated in vivo in the ovine stifle joint (Tapper et al, 2002). Our objective in this study was to investigate the role of the intact and healing ligaments during walking, incline walking, and trotting. Our first hypothesis was that ligament transection would cause changes in joint kinematics that would become more pronounced with increasing levels of exercise intensity. Our second hypothesis was that intact ligaments would be recruited to stabilize the partially transected joint.

METHODS

Eight skeletally mature trained Suffolk sheep were studied. Five sheep received combined transection of the anterior cruciate and medial collateral ligaments, and three sheep received sham surgery. The in vivo stifle joint kinematics were measured in the intact joint, and at 2 and 20 weeks after surgery. Kinematics were recorded for thirty strides during walking (2mph), incline walking (2mph), and trotting (3.5mph) on a standard treadmill. A rigid surgically implanted bone marker system (Figure 1) was used to define the 3D positions of the tibia and femur during the in vivo motion. The spatial positions of the bone markers during gait were recorded using a 4-camera high-speed (120Hz) video based motion analysis system (Expert Vision, Motion Analysis Corporation). Following euthenization, a 3D digitizer (FaroArm, Faro Technologies Inc, accuracy ±0.05mm) was used to define anatomically based coordinate systems within the tibia and femur (Figure 2). The bone markers positions, bone geometry, and locations of ligament insertions (ACL, PCL, MCL, LCL) were then digitized relative to the anatomical coordinate systems in each bone.

RESULTS AND DISCUSSION

The distances between insertions of the ACL, MCL, LCL, and PCL were significantly changed after transection during walking, incline walking, and trotting in all five

Figure 1: Lateral view of the right stifle joint after dissection, showing the implanted bone markers and the transformations used to determine the joint position.

Figure 2: Anterior view of the right stifle joint, showing the orientation of the anatomical coordinate systems.

A subject specific geometric model of the joint was developed using the digitized joint surface and ligament geometry. The in vivo kinematics were then used to create a 3D animation of the joint surfaces and ligaments for visualization of the changes following ligament transection (Figure 3).

Figure 3: Model of the ovine stifle joint during walking showing the bone surfaces and four major ligaments.

Joint angles and tibial translational positions were described using a joint coordinate system (Grood and Suntay, 1983). The 3D Euclidean distance between ligament insertions was calculated. For each specimen, the in vivo kinematics at 2 and 20 weeks after surgery were compared with those of the intact condition using a standard t-test (p<0.05). A Pearson’s test was used to assess the correlation between changes in joint position and distances between ligament insertions.
experimental sheep. In general, the magnitude of the changes resulting from ligament transection was much larger than the differences observed between walking, incline walking, and trotting. The three sham operated sheep also showed significant changes in the distances between ligament insertions after sham surgery. The magnitude of these changes was small relative to the changes observed in the distances between ACL and PCL insertions in the experimental sheep. For the MCL and LCL, the changes were of a similar magnitude to the smaller changes observed in some of the experimental sheep. These significant changes may occur in response to the sham surgery, or alternatively may represent true variability in joint motion on different test days. Previous investigation of differences in the kinematics of the intact joint between different test days showed that the changes between days were smaller than the variability on one test day.

The distance between insertions of the ACL increased significantly at both 2 and 20 weeks after transection in all five transected sheep (Figures 4 and 5). In three of the five sheep the distances increased with time from 2 to 20 weeks, in one sheep there was some recovery at 20 weeks, and in the remaining sheep, there was no significant change. At 2 weeks, incline walking did not change the distance between ACL insertions compared with walking in three sheep. In two sheep, the distance decreased significantly. By 20 weeks, after transection the increase in distance was significantly smaller during incline walking compared with walking in three sheep, with no significant difference in the remaining two sheep. When running and walking were compared at 2 weeks, the increase was greater in only one sheep during running, less in two sheep, and unchanged in the remaining two sheep. At 20 weeks, running caused a smaller increase in three of the five sheep, with no difference in the remaining two sheep.

The distance between MCL insertions was significantly increased at 2 weeks after transection in only one sheep, decreased in two sheep, and the response was dependent on exercise intensity in the remaining two sheep (Figures 6 and 7). At 20 weeks, the distance between MCL insertions was increased in three sheep and decreased in two sheep for all levels of exercise intensity. Significant changes existed between the distances during the three levels of exercise intensity, however these changes were highly subject specific and showed no consistent patterns.

The changes in distance between LCL insertions were similar at 2 and 20 weeks, with four sheep showing a decrease in the distance after transection, one sheep showing an increase (Figures 8 and 9). The differences between walking, incline walking, and running were generally small and variable between subjects.

The pattern of changes in distance between PCL insertions was very similar to those observed for the LCL (Figures 10 and 11). At 2 weeks, the distance between PCL insertions decreased in four sheep and increased in one sheep. At 20 weeks, the distance decreased in three sheep, increased in one sheep, and was dependent on the exercise condition in the remaining sheep. The impact of exercise intensity was small and variable.

SUMMARY

Ligament transection caused significant changes in joint kinematics during walking, incline walking, and trotting. In accordance with findings of previous studies (Korvick et al, 1994; Tashman and Anderst, 2001), the distance between ACL insertions was consistently increased at 2 weeks after ACL/MCL transection, and this increase was sustained at 20 weeks. In contrast, although the MCL was transected, the distance between MCL insertions was not consistently increased. Although significant changes were observed in all sheep, the response was subject specific, with both increased and decreased distances observed.

In addition to the changes observed in the transected ligaments, significant changes were observed in the remaining intact LCL and PCL. These changes were subject specific, however, for the majority of the sheep studied there was a decrease in the distance between insertions after ACL/MCL transection.

These findings suggest that although the stress state in the remaining intact ligaments is changed after transection, these ligaments do not appear to be recruited to stabilize the joint. The 3D kinematic model demonstrates the orientation of the ligaments with respect to the articular surfaces. In previous analysis of the in vivo kinematics before and after ACL/MCL transection (Tapper et al, 2002), a significant anterior tibial shift was seen during the stance phase of walking. The ACL passes downwards and anteriorly as it passes from the femur to the tibia. In this orientation, an anterior tibial shift is expected to increase the distance between ACL insertions. The changes in distance between ACL insertions were positively correlated with the anterior tibial shift in all five sheep (r: 0.861 to 0.997, p<0.01). The MCL is oriented almost vertically, perhaps explaining the variability in the direction of the changes during the anterior tibial shift. In contrast, both the LCL and the PCL pass upwards and forwards from the tibia to the femur. In this orientation, the distance between their insertions would be expected to decrease during an anterior tibial shift. The changes in distance between PCL insertions were negatively correlated with the change in anterior tibial shift for four of the five sheep (r: -0.721 to -0.993, p<0.01). The changes in distance between LCL insertions were positively correlated with the changes in distance between PCL insertions (r: 0.315 to 0.968, p<0.01).

As exercise intensity was increased from walking, to incline walking and running, significant changes were observed for some subjects, however there were no consistent patterns. The magnitude of changes resulting from ligament transection was generally much greater than the differences observed between the walking, incline walking, and running. A key finding from these results is the high degree of variability in the response to transection for different subjects. This between-subject variability is much greater than the variability in the kinematics recorded for one sheep at one test session, or for one sheep at different test sessions. In addition, parallel studies of the joints of these sheep have shown osteoarthritic changes in the stifles joint at 20 weeks after transection, which appear to be subject specific. One of the goals of this model is to relate the mechanical and
biological changes in the joint. In order to achieve this goal it appears necessary to study the changes in the joints on a case-by-case basis rather than using pooled data for statistical analysis.

ACL/MCL transection removes two of the primary passive stabilizers of the stifle joint. In addition to these two structures, the joint may be passively stabilized by the remaining ligaments, the joint capsule, the meniscus, joint effusion or joint contact, or actively stabilized by the periarticular muscles. Variations in the response of different sheep to ACL/MCL transection may occur due to differential recruitment of the passive structures, or perhaps variations in the dynamic muscle control of joint motion. Additional experimental investigation is necessary to investigate the source of the inter-subject variability in joint kinematics after ligament transection.

In conclusion, ligament transection caused significant changes in joint kinematics as demonstrated by the significant changes in the distance between ligament insertions. These changes were not consistently magnified with increasing levels of exercise intensity. Furthermore, after ACL/MCL transection, the intact ligaments do not appear to be recruited to stabilize the joint.

REFERENCES

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Lesley Jacques, Linda Marchuk, Mike Lovas
Figure 4: Maximum change in distance between ACL insertions at 2 weeks after ACL/MCL transection.

Figure 5: Maximum change in distance between ACL insertions at 20 weeks after ACL/MCL transection.

Figure 6: Maximum change in distance between MCL insertions at 2 weeks after ACL/MCL transection.

Figure 7: Maximum change in distance between MCL insertions at 20 weeks after ACL/MCL transection.
Figure 8: Maximum change in distance between LCL insertions at 2 weeks after ACL/MCL transection

Figure 9: Maximum change in distance between LCL insertions at 20 weeks after ACL/MCL transection

Figure 10: Maximum change in distance between PCL insertions at 2 weeks after ACL/MCL transection

Figure 11: Maximum change in distance between PCL insertions at 20 weeks after ACL/MCL transection