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The Pivot Shift Test Modelled By Catastrophe Theory Corresponds To A Cusp Catastrophe

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Abstract

There is currently a lack of a 'Gold Standard' for quantification and modelling of the Pivot Shift test (PST) in anterior cruciate ligament (ACL) deficient knees. A sudden change in state resulting from a small change in a parameter is characteristic of systems that can be modelled using catastrophe theory. Analysis of data obtained from 50 consecutive navigated ACL reconstructions demonstrated statistically significant ($p < 0.01$) fitting with a cusp type model of catastrophic failure. Modelling the PST as a Cusp catastrophe may enable true evidence based decisions as to which ACL deficient knees should have surgery and guide the decisions as to the optimum type of surgery required. It may also influence the position of the reconstructed ligaments and allow objective comparisons of different ligament types and surgical techniques.

Introduction

Describing a reliable mathematical model for a phenomenon first requires accurate measurements. The key test of knee joint laxity following a ruptured anterior cruciate ligament (ACL) is the Pivot Shift Test (PST). This is done manually and there is poor inter observer reliability (Donaldson, Warren and Wickiewicz, 1985). There is currently a lack of a 'Gold Standard' for quantification and modelling of the Pivot Shift test (PST) (Lopomo, Zaffagnini and Amis,2013).

. In the literature 25 parameters have been used to describe the Pivot shift test (PST). These have generally measured antero-posterior translation, acceleration and rotation. The mathematical relationship between the various parameters has hitherto not been clarified (Ahldén et al, 2012). However, it is acknowledged that it is the sudden acceleration of anterior- posterior movement

resulting from a very small change in flexion during the test that is of clinical significance. A sudden change in state resulting from a small change in a parameter is characteristic of systems that can be modelled using catastrophe theory.

The aims of this study were to to quantify the movements of the anterior cruciate deficient knee, to determine whether the Pivot Shift in the anterior cruciate deficient knee can be modelled accurately using catastrophe theory, and if so, to determine what subset of catastrophe type best fits the measurements and whether the catastrophe model did not fit after ACL reconstruction (ACLR).

Methods

The PST was performed on 50 consecutive MRI confirmed ACL deficient knees by the senior author at surgery prior to and after navigated ACL reconstruction using the Orthopilot® ACL V3 system (BBraun, Tuttlingen). The study received appropriate ethical approval and the patients gave informed consent.

Under general anaesthesia, passive arrays were screwed into the distal femoral metaphysic and proximal tibial metaphysis respectively. Registration of the anatomical points was performed as per the standard Orthopilot® navigated ACL technique. The patient was positioned with the legs hanging over the end of the operating table. The affected leg was picked up by the heel. The postero-lateral aspect of the tibial metaphysis was passively supported on the examiner's other hand while a simultaneous internal rotation torque was applied to the upper tibial metaphysis. This manoeuvre resulted in gravity causing the distal thigh to tend to sag posteriorly relative to the tibia independently of the surgeon's skill. The knees were taken through a continuous range of extension to flexion for a series of internal/external angles. Internal/external rotation (degrees), flexion/extension (degrees) and antero-posterior translation (mm) were simultaneously recorded using the navigation software. This was done prior to and repeated after ACL reconstruction. The data was automatically recorded by the navigation software as .csv files. The data was imported into the R statistical system and fitted to the "Cusp" package by the third author, RPPPG. Automatic model fitting was done to linear, logistic and cusp models. Evaluation of each fit was automatically made using the Akaike Information Criterion (AIC), Akaike Information Criterion with a correction for small sample sizes (AICc) and the Bayesian Information Criterion (BIC). The results were statistically interpreted by the second author of the paper, LC.

Results

The male/female ratio was 37/13. The right/left ratio was 30/20. The mean age was35.6 years (std dev 1.3). Before ACLR the mean anterior movement was 11.5mm (std dev 0.56). After it was 3.2mm (std dev 0.33). Before ACLR the mean range of tibio-femoral rotation was 27.3 degrees (std dev 4.9). After it was 15.1 degrees (std dev 3.6). The results of the AIC, AICc and BIC were used to determine the most appropriate model. The PST of all 50 ACL deficient knee was best modelled as a Cusp type (Grasman et al, 2009) Catastrophe (Cobb, 1978). (Figure1)

Analysis after stabilisation confirmed the absence of catastrophic behaviour. The fitted model clearly reproduces the sudden acceleration of anterior-posterior movement as flexion crosses the singularity, and all estimated parameters were significant at the $p < 0.01$ level. Based on this model, there are at least three subcategories of knee behaviour as revealed by cusp catastrophe modelling of the PST.

Conclusion

Modelling the PST as a Cusp catastrophe may enable true evidence based decisions as to which ACL deficient knees should have surgery and guide the decisions as to the optimum type of surgery required. It may also influence the position of the reconstructed ligaments and allow objective comparisons of different ligament types and surgical techniques. Catastrophe theory based modelling of this type could possible also be extended to model other joint subluxation/dislocations in natural and prosthetic shoulders, hips and the patella-femoral joint.

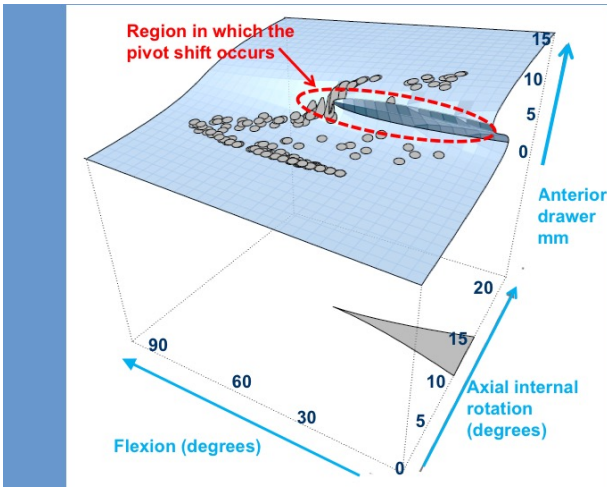

Figure 1: Point cloud showing the region in which the Pivot Shift occurs.

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