Quantitative assessment of anterior cruciate ligament deficiency: Applied load versus applied displacement

P N Grimshaw and P Bowker

Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 1997 211: 441
DOI: 10.1243/0954411981534565

Quantitative assessment of anterior cruciate ligament deficiency: applied load versus applied displacement

P N Grimshaw[1] and **P Bowker**[2]
[1]School of Education, University of Exeter
[2]Faculty of Health Care and Social Work Studies, University of Salford

Abstract: The Salford static knee instrument (SSKI) was developed to determine the quantitative assessment of the human knee joint *in vivo* by utilizing the technique of applied displacement and measurement of resistive load as proposed by Butler *et al.* (**1**). The instrument was used in parallel with the device developed by Al-Turaiki (**2**) which utilized the opposite method of assessment. The objective of the research was to examine which of the two techniques provided the more reliable and accurate method of knee assessment. Fourteen patients with suspected isolated rupture of the anterior cruciate ligament (ACL) were subjected to anterior–posterior drawer testing on both devices. The results showed that each instrument produced results which confirmed the clinical diagnosis by indicating a significant decrease in anterior stiffness when comparing the injured and uninjured knees. [SSKI device ($p = 0.000$) and Al-Turaiki (**2**) device ($p = 0.002$) statistical significant difference testing with Bonferonni Alpha correction $p = 0.0125$]. The results showed the Salford static knee instrument indicated a 58 per cent decrease in anterior stiffness and the Al-Turaiki (**2**) device a 35 per cent decrease when comparing the injured and uninjured knees. In conclusion it is suggested that the application of displacement and measurement of load as proposed by Butler *et al.* (**1**) may be the most appropriate technique for precise clinical diagnosis of pathological human knee joint instability.

Keywords: load, displacement, knee, anterior, stiffness

1 INTRODUCTION

Butler *et al.* (**1**) proposed that accurate qualitative and quantitative assessment of the knee can only be provided by applying a fixed displacement and measuring the resistive load. Ligaments limit motion of the joint by development of a restraining force when stretched [Brantigan and Voshell (**3**)]. The total restraining force is the sum of the individual ligament forces in the absence of muscle forces, weight-bearing forces and other similar factors. Controlling joint displacement controls the amount of ligament stretch and hence its force. Reproducing the displacement reproduces the force in each ligament.

By contrast, other studies have examined ligament function by measuring the joint displacement resulting from application of a known load. This does parallel the clinical test (such as the Lachman test), which aims to assess the degree and type of injury from the observed laxities. However, the amount of joint laxity depends upon the magnitude of the applied load and the complex interaction among all the ligaments present. When a ligament is cut or injured, the interaction changes, causing an increase in laxity which depends on the loss of restraining force in the cut ligament and the change in interaction in the remaining ligaments. This does not directly indicate the function of the cut or injured ligament. Instead, the increase in laxity after the cut or injury is due to the action of the remaining ligaments acting in a new relationship to each other (**4**–**8**).

One of the most prominent works on *in vivo* knee instability was carried out by Markolf *et al.* (**9**) who developed an apparatus which was capable of measuring anterior–posterior force versus displacement during manual manipulation of the knee. The device developed applied a known load and measured the resulting displacement of the joint. In this work 28 male and 21 female subjects, each of whom had no previous record of knee pain, were assessed. The anterior–posterior drawer test was conducted in 0, 20 and 90° of flexion and terminal stiffness and laxity was determined at 200 N of force. The results revealed that the greatest anterior–posterior laxity (5.5 mm) was observed at 20° of knee flexion and that individual right–left differences averaged 26–35 per cent for laxity and 19–24 per cent for stiffness. These

The MS was received on 17 June 1996 and was accepted for publication on 25 July 1997.

differences were felt to be clinically significant although they had not been previously viewed as such by an examining surgeon or physician.

Al-Turaiki (**2**) developed equipment very similar to that used by Markolf *et al.* (**9**) which enabled the *in vivo* quantitative assessment of human knee joint instability. The instrument applied a quasi-static load (up to 120 N in the anterior–posterior drawer test) and measured the observed displacement. Anterior–posterior drawer tests in 20° of knee flexion on 31 normal subjects produced values for left and right knees respectively of total laxity 5.1 mm and 4.9 mm, anterior stiffness 22.7 N/mm and 23.7 N/mm and posterior stiffness 31.9 N/mm and 33.8 N/mm.

Daniel *et al.* (**10**) reported the development of a commercially available portable arthrometer (the Medmetric KT2000). The work assessed 33 cadaver specimens, 338 normal subjects and 89 patients with unilateral disruption of the anterior cruciate ligament (ACL). The KT2000 is used to apply a controlled load to the joint and measure the amount of anterior and posterior laxity. During the test, forces are applied by hand through a force-sensing handle, located 10 cm distal to the joint line. The data output is printed on an *x/y* plotter in the form of applied force against tibial displacement. The study measured total anterior–posterior laxity at an anterior–posterior load of 89 N. In summary the results showed anterior displacement at 89 N was 5.7 mm in a group of normal subjects and 13.0 mm in a group of patients with a disrupted ACL. Some of the conclusions from this work disagreed with the findings of the earlier work by Markolf *et al.* (**9**). The KT2000 is a clinically applied tool and its reliability has been confirmed in the work by Hanten and Pace (**11**).

Dahlkvist (**12**) developed a comprehensive piece of equipment which enabled three tests of instability to be carried out in any combination and at any angle of knee flexion. The apparatus was controlled completely by a microprocessor and the loads were applied by controlled servo and stepper motors. Testing was carried out on 81 normal knees and 47 patients with ligamentous or meniscal injuries.

The right–left differences of 23 normal subjects measured at 20° and 90° were compared and correlated with anthropometric data. The mean absolute right–left variation was close to zero, and the data fitted a normal distribution. However, the relative right–left differences (absolute right–left difference/stiffer knee value) were considered to be of greater clinical importance. The study also reported the results of tests carried out on 47 patients with injury to the knee, mainly ACL, medial collateral ligament (MCL) or meniscal injuries. The relative differences between injured and uninjured knees were calculated for all the measured variables, and compared with the same results obtained from the 'normals' group. Significant differences between the injured and normal groups were found for only four variables. Following ACL injury, a 37 per cent drop in the tibial rotational stiffness and a 30 per cent drop in anterior–posterior stiffness were recorded. In addition, an increase in anterior drawer laxity of 48 per cent (2.3 mm) was found.

Shinno *et al.* (**13**) described the development of an apparatus which was used to measure the anterior instability of the knee. The device applied anterior–posterior forces of up to 250 N with an angle of 20° of knee flexion. Laxity was determined at 200 N of load while stiffness was calculated at 50 N. The stiffness calculation at 50 N is unusual in that it represents the general stiffness associated with the joint and is not one which would seem to be the most diagnostic for ligamentous injury.

Work was carried out on three cadaver knees, 61 normal male and female subjects and 92 patients with chronic unilateral deficiency of the ACL. The 92 patients consisted of 25 with isolated lesions of the ACL, 56 with anterior cruciate and associated torn meniscus injuries and 11 with anterior cruciate injuries which were associated with a chronic tear of the medial collateral ligament. For the 61 normal subjects, no significant difference was apparent between their two knees as regards anterior laxity, anterior stiffness and total laxity. However, the 92 patients with unilateral ACL ruptures demonstrated significant differences in all of these test variables.

Despite the various devices available, it is still apparent that a degree of confusion exists as to the exact interpretation for clinical diagnosis. For example, differences in stiffness, right–left differences and large or small increases in laxity all seem to have diagnostic value but at different magnitudes across the variety of studies available. The objectives of this research are to examine two methods of quantitative assessment of knee instability (applied load and applied displacement) in order to determine which method produces the most accurate and reliable results for ligamentous assessment of knee instability.

2 METHODS

Continuing from the work of Al-Turaiki (**2**), the SSKI was designed and developed in order to examine the approach of applying displacement and measuring resistive loads as proposed by Butler *et al.* (**1**), in comparison with the previously employed technique of applying loads and monitoring the resulting displacements.

The Al-Turaiki (**2**) instrument consisted of a modified dental chair in which the subject sat with the femoral condyles located in position by adjustable clamps both medially and laterally. The thigh of the leg to be tested is placed in a padded gutter and a loose sandbag is placed over the patella. Both thigh and sandbag are covered by a pneumatic cuff which is inflated to a certain pressure during the test. The securing of the patella is assumed to secure the femur and prevent it rotating during the test. Finally, the foot and ankle are held firmly on an angled plate with the malleoli clamped by sandbags and the foot held by an adjustable strap.

In the anterior–posterior drawer test which is conducted in 20° of knee flexion, an additional strap is placed around the leg at mid-tibial level. An anterior preload of 2 kg (20 N) is applied to counteract the effect of gravity. Loads of 2 kg (20 N) are then applied to a maximum of 12 kg (120 N). The load applied is measured by two load transducers which are incorporated within a pulley system, while the resulting displacement is measured by a linear potentiometer which is placed lightly against the tibial tuberosity. By amplification and the use of an *x/y* plotter it is then possible to measure the resulting displacement against the load applied.

Fourteen patients with suspected isolated rupture of the ACL of one knee were subjected to instability testing on the knee instability instrument developed by Al-Turaiki (**2**) and on the SSKI. The patients were all male subjects with an age range of 19–44 years (mean 30.2). All the patients had been referred for examination by consultant orthopaedic surgeons and all had undergone arthroscopic and clinical examination. No patient had bilateral injury and all the injuries occurred while participating in sport. In addition, written informed consent and ethical approval was obtained for all subjects undergoing examination, for both instruments.

2.1 Design and development of equipment (SSKI device)

2.1.1 Seating and system of clamping

The seating for the patient took the form of a bench system which had the seat base angled upwards at 15° to the horizontal and the back rest permanently fixed at an angle of 55° to the horizontal so as to produce an angle of 110° of hip flexion. With this specific positioning of the patient, adequate relaxation of the hamstring muscles during testing was achieved. A range of knee motion from 90° of flexion to full extension was permitted during testing (Fig. 1).

A datum plate was fixed firmly to the bench system. The thigh holder and femoral clamping system were fixed to this plate by a series of screws located both underneath and above. The accurate location of the plate, thigh holder and clamping system permitted precise positioning of the femur and the knee joint in relation to the testing apparatus. The thigh holder was designed as an interchangeable unit which could be fixed firmly to the datum plate. Three different sized holders were available to accommodate the range of muscle girths. Velcro straps were attached to the thigh holders and the whole unit was covered in a flexible sponge-type material. A pneumatic thigh cuff was used to clamp the limb. This eliminated any intrinsic stability resulting from contraction of the quadriceps femoris muscle group (**9**, **14**, **15**). The cuff was strapped firmly to the thigh using Velcro straps and inflated during testing to a pressure of 100 mmHg.

The knee joint was located over the central pivot of the testing apparatus, and all the screw adjustments on the clamping mechanism were designed to be hand tightened for safety, ease of operation and for speed of clamping and unclamping. The femoral condylar clamp screws were covered with sand-filled leather pouches of sufficiently large diameter to reduce any pain and to provide

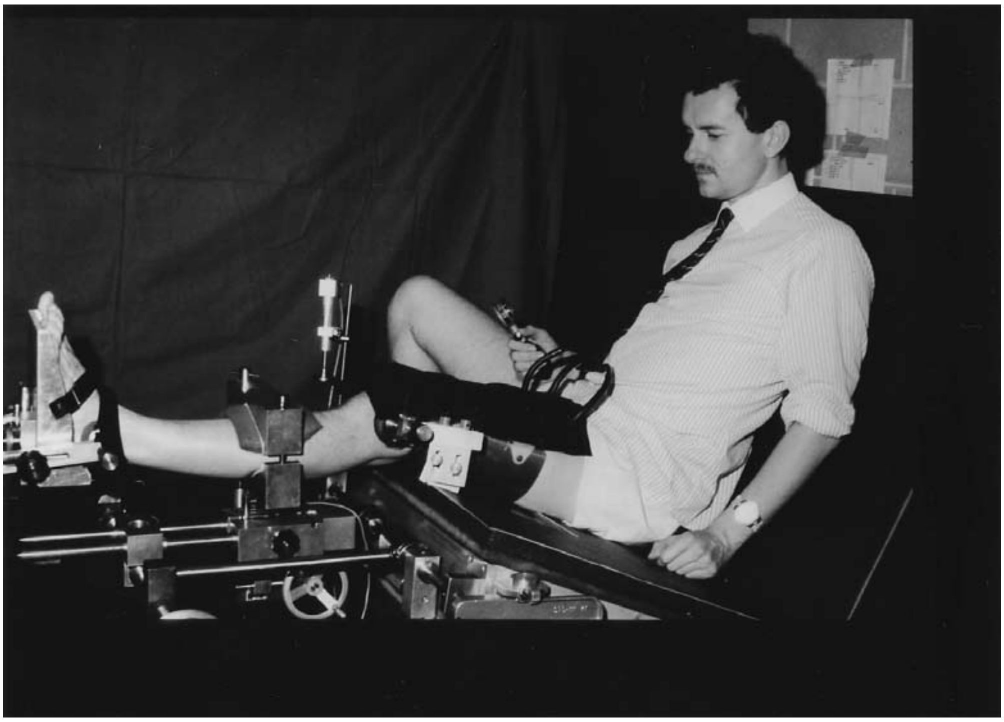

Fig. 1 The Salford static knee instrument

minimum movement of the skin–bone complex. These sand-filled pouches were found to be most suitable for this purpose. In addition, the pouches used in this work were adjustable with a further six degrees of freedom to allow for the incongruent nature of the femoral condylar geometry (Fig. 2).

The lower leg section was positioned in a unit which allowed the foot and ankle arrangement to be clamped. The device was adjustable and could slide forward or backward depending upon leg length. The foot was strapped by Velcro straps to a datum plate and was allowed to assume its natural amount of internal or external rotation. The foot holder system was then locked and the malleoli clamps were located in position, again utilizing a hand-tightened system and sand-filled leather pouches. The foot was then firmly held in position. When the patient was clamped in the correct position with the knee joint located directly over the central pivot, further support behind the back was made available if required. The considerable width of the seating area allowed an easy change-over from testing of one leg to the other.

Many patients who had experienced both the Al-Turaiki (**2**) instrument and the SSKI apparatus stated that the SSKI device was both aesthetically more pleasing and by far the more comfortable of the two models. Furthermore, patients stated that, although more comfortable, they felt that the knee was being held more securely. Generally this was more acceptable from a psychological and scientific measurement perspective.

2.1.2 Anterior–posterior drawer testing

The anterior–posterior drawer testing system consisted of a hand wheel and gearbox arrangement which was fixed to a slider support block which in turn housed the measurement equipment (Fig. 2). The gearbox, operated by a hand-wheel, makes one complete revolution and the output diameter makes a half revolution turn. As the hand-wheel makes one revolution, the screwed rod which is attached to the gearbox is advanced or retracted in an anterior–posterior drawer in increments of 1 mm. An anti-backlash wheel was incorporated in the gearbox mechanism which prevented any unnecessary backlash during the transfer from anterior to posterior drawer movement.

A strain gauge load transducer is permanently fixed to the end of the screwed rod. This load transducer is also fixed to the lower aspect of the tibial clamp holder, which is also a part of the anterior–posterior drawer assembly. The load transducer is used to monitor the load transferred down the screwed rod, which is offered in resistance to the anterior–posterior drawer movement by the knee joint. The transducer is also used to monitor the application of the required anterior preloading on the limb which compensates for the effects of gravity. This was determined to be 20 N anterior preload in both methods of test [SSKI and the Al-Turaiki (**2**) device]. A linear potentiometer is attached to the side of the lower tibial clamp holder (Fig. 2) and further located on a datum attached to the gearbox. The device is spring loaded to permit multidirectional testing. In this manner it is possible to monitor the exact amount of anterior or posterior drawer imparted to the limb.

The slide support system which holds the lower tibial clamp, the gearbox, the load transducer and the linear potentiometer can be moved along the steel rail assembly. The device is usually positioned and locked at about 6 cm distal to the tibial tuberosity.

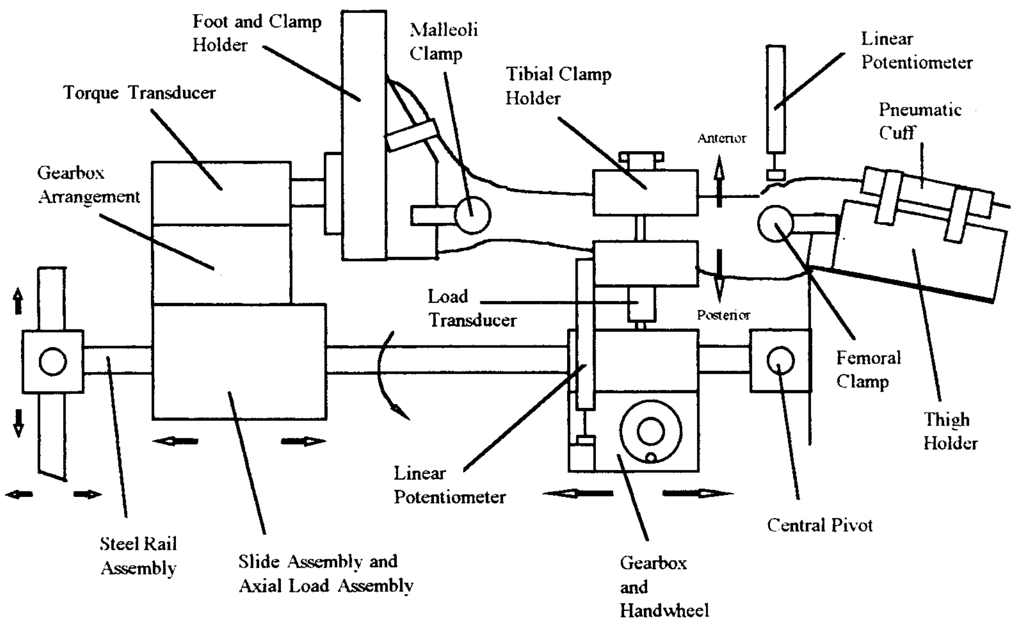

Fig. 2 Schematic diagram of the SSKI device showing the anterior–posterior drawer mechanism

The top section of the tibial clamp holder is placed over the limb with a sand bag inserted between the clamp and the skin surface. This sand bag allows for different shapes of limb and for the testing of the contra-lateral leg, when the majority of the gastrocnemius muscle will then be located on the opposite side. As the upper portion of the clamp and the sand bag are placed on the limb, two locking screws are inserted and tightened. Once securely tightened with the correct preload, the limb is firmly held. Any unnecessary movements between skin–bone, sand bag and clamp are at a minimum.

In addition, another linear potentiometer can be located on the patella during the testing. The output of this potentiometer is subtracted from that of the primary measuring potentiometer located on the slide holder. In this way the true movement of the tibia relative to the femur is obtained. The advantage of using the patella monitoring system became apparent when patients with severe injury were examined. These patients were often unable to be clamped as securely as less seriously injured patients and the consequence of femoral movement during testing was significantly increased. The patella monitoring system was able to detect this movement and if excessive (>1 mm) it could be corrected by turning the hand-wheel.

The lower tibial clamp section holds the foot and incorporates two malleoli clamps which are fully adjustable. The foot holder is also allowed to rotate and allow the natural degree of internal–external rotation of the tibia during the anterior–posterior drawer test. Throughout the test the foot is held firm by Velcro straps, the rotation of the foot holder is locked and the malleoli are lightly clamped.

In the anterior–posterior drawer test the limb is subjected to an anterior drawer of 5 mm and a posterior drawer of 5 mm. This displacement is consistent with the normal amounts of displacement observed within the intact knee as identified by Daniel *et al.* (**10**) and is considered within safe tolerable physiological limits for pathological knees. The displacement of the limb is applied in a quasi-static operation by incremental turning of the hand-wheel. The rate of loading or displacement was equivalent for both instruments. The limb is first loaded (or displaced) in one direction, unloaded, then loaded and unloaded in the opposite direction. This process is then repeated until a complete closed-loop hysteresis response curve is obtained. Figure 3 illustrates a typical hysteresis response curve in more detail.

The electrical outputs from the potentiometers and transducers are amplified and then electronically interfaced into the analogue to digital port of a microcomputer. Once in digital form, the data set is taken into a computer program which is operated by a series of menu commands.

The instrument is able to examine the limb in various modes of testing which include anterior–posterior drawer, medial–lateral drawer, internal–external rotation and varus–valgus rotation in any degree of flexion from 90° to full extension, both with and without axial joint loading.

2.1.3 Reproducibility and repeatability

The reproducibility of the apparatus was obtained by examining the same normal subject using the anterior–posterior drawer test on eight completely separate occasions. The coefficients of variance obtained for all variables gave maximum values of 9.7 per cent. Repeatability values were obtained by examining the same normal subject ten times on the same occasion. The coefficients of variance for all variables in the anterior–posterior drawer test had maximum values of 7.8 per cent. Table 1 presents similar test values as determined by other research workers (**2**, **9**, **10**).

3 DATA ANALYSIS

The results were presented as closed-loop hysteresis response curves with applied displacement measured in millimetres (mm) plotted on the x axis and resistive load measured in Newtons (N) on the y axis. The curve is derived from the application of a fixed displacement and the measurement of the resistive load.

Stiffness is determined in the mathematical application of a third-order regression analysis. The results are interpolated and stiffness is calculated as general, mid-range and terminal values. General stiffness is obtained from the gradient of the entire loading–displacement curve, while mid-range stiffness is derived from a value of 0–2.5 mm. Terminal stiffness is calculated between values of 2.5 and 5 mm of displacement. Terminal stiffness was found to be the most marked indicator for the diagnosis of an isolated ruptured ligament. Values for resistive load in each direction and the energy loss tangent were also available from analysis of the data.

Terminal stiffness is believed to be representative of the stiffness value which is the most appropriate for the diagnosis of isolated ligamentous insufficiency. At this particular level of loading or displacement the ligament is believed to be operating at, or near to, its maximum

Table 1 Reproducibility and repeatability (coefficient of variance: maximum values) of quantitative knee assessment devices as determined by other research workers and the SSKI device

Researchers	Anterior–posterior drawer: Reproducibility (%)	Anterior–posterior drawer: Repeatability (%)
Markolf *et al.* (**9**)	33	N/A
Al-Turaiki (**2**)	17	8
Dahlkvist (**12**)	Less than 10% on all test variables	
This study (SSKI device)	9.7	7.8

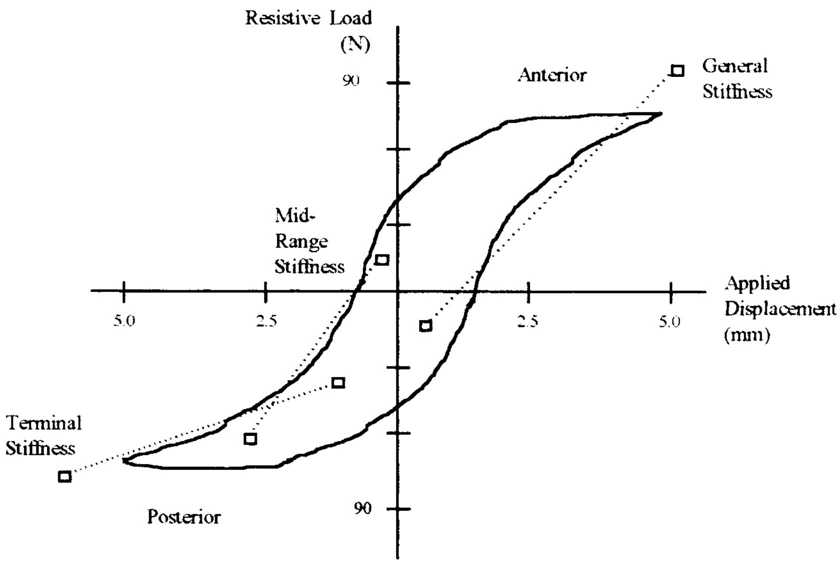

Fig. 3 A closed-loop hysteresis response curve with the measures of mid-range, terminal and general stiffness identified

resistive nature. In addition, it is believed that this is the position at which the ligament is at its most vulnerable.

It is clear that the measures of general and mid-range stiffness are still important in the diagnoses of complex injury cases and should be used for a complete diagnosis of injury. Shinno *et al.* (**13**) stated that the most marked indicator of cruciate ligament injury was seen in stiffness calculated at up to 50 N of loading. It could therefore be stated that in order to examine isolated or complex injury cases, assessments need to consider all the stiffness ranges of the knee.

Specific indicators for diagnoses of patterns of ligamentous instability have been presented by many workers, by examining a group of specific injury patients and examining the most marked differences. From such an analysis it is possible to determine the specific variable which is the most marked indicator and the significance of the difference between the two knees for this variable.

Unique to the SSKI is the presentation of resistive load values as opposed to directional laxity. As a result of the nature of the testing procedure it is impossible to state values for directional laxity. Therefore, resistive load values are stated for the maximum preset applied tibial displacements. This method of presentation may be confusing because only Butler *et al.* (**1**) present their data in this manner. However, examination of the literature will reveal that laxity values are not a clear indicator for ligament deficiency and, although universally comparable, they do not indicate accurately the state of the joint's condition. This was further reinforced by the work of Dahlkvist (**12**), who determined that a loss of anterior stiffness was the most marked indicator for ACL deficiency. Hence, resistive load values may prove to be more meaningful with respect to the diagnosis of injury.

4 RESULTS

4.1 Comparison of results of two static knee instability testing instruments: Al-Turaiki (2) and the SSKI device

Since the two instruments are different [the instrument developed by Al-Turaiki (**2**) applies load and measures displacement] and do not present similar measurements for laxity, it is only appropriate to carry out analysis on the stiffness values. The statistical analysis used was carried out on the VAX mainframe computer utilizing the SPSSx statistical package. All the patients underwent anterior and posterior drawer testing on both instruments and on both legs in 20° of knee flexion.

4.2 Statistical analysis

The instrument developed by Al-Turaiki (**2**) applies load to a maximum of 120 N and then calculates the result in displacement, whereas the SSKI applies 5 mm of displacement and measures the resistive loading, hence the two instruments are different in their approach to knee assessment.

Both applications are of different magnitudes and the SSKI, by its mechanical nature (application of 5 mm of tibial displacement) produces resistive load values that are lower than the 120 N applied by the Al-Turaiki (**2**) device. Therefore, it is only necessary to compare the two sets of results individually for the two separate techniques. The statistical testing in this example incorporated *t*-testing with Bonferroni alpha correction for inequality ($p = 0.0125$). The result would reveal if one technique was particularly more or less sensitive than the other in its application and its measurement of the same two knees. In this manner it was possible to determine whether the technique of applying displacement and measuring load (as in the SSKI) was significantly more sensitive than or different to the technique of applying load and measuring displacement [as in the Al-Turaiki (**2**) instrument].

It is important to point out a certain criticism regarding this method of analysis. Since the results from the two instruments cannot be directly compared statistically, it could be argued that the higher loading levels of the Al-Turaiki (**2**) instrument may be responsible for any observed difference in the results. Hence, the analysis is not examining directly the two techniques of measurement but instead it is examining the different loading and displacing levels. Indeed, in the normal results determined by Al-Turaiki (**2**) it is possible to observe that for 120 N of anterior and 120 N of posterior loading the total laxity of the joint was 5 mm. In the application of the SSKI the total laxity imparted to the limb would be 10 mm (5 mm anterior displacement and 5 mm posterior displacement). If the characteristics of the knee joint were perfectly linear, the resistive load levels in the SSKI would be expected to be twice those of the Al-Turaiki (**2**) device (240 N) for the normal knee joint. The mechanical properties of the knee joint are not, however, linear in this respect and hence different results will be produced. However, comparing the data for the uninjured and injured limbs for the two instruments individually should produce similar results unless the techniques are clearly demonstrating different patterns of injury or stiffness. This would, in itself, be an important clinical finding.

Table 2 shows the mean values for terminal stiffness as measured on the Al-Turaiki (**2**) device and SSKI. In all the tests the SSKI demonstrated greater percentage difference values for all the test variables examined. The most marked indicators being a 58 per cent decrease in anterior terminal stiffness when comparing the uninjured and injured limbs. In addition, the device produced a figure of 48 per cent decrease in anterior resistive load in the injured compared to the uninjured limb.

The Al-Turaiki (**2**) instrument demonstrated a value of 35 per cent decrease for anterior terminal stiffness and a 30 per cent increase for anterior laxity. With reference to posterior stiffness and laxity/load, both instruments showed marginal changes with the injured limb being less stiff and more lax, or less resistive, in each case.

The mean values clearly show that the SSKI device appears to be more sensitive to the change in the knee joint following a ligament injury. Carrying out statistical significant difference testing between the injured and uninjured limbs for both instruments produces the results presented in Table 3. The results indicate that the SSKI produces values which are clearly more statistically different at a higher level of significance than those for the Al-Turaiki (**2**) test. The probability of difference for anterior stiffness on the SSKI is $p = 0.0001$ as opposed to $p = 0.002$ on the Al-Turaiki (**2**) instrument. This tends to suggest that more statistical confidence can be attributed to the results from the SSKI device.

An interesting finding is that the significant difference testing for posterior stiffness regarding the two instruments shows no significant difference between the two legs. The Al-Turaiki (**2**) instrument produces a probability of $p = 0.768$ while the SSKI device produces a probability of $p = 0.056$. Clearly, the Al-Turaiki (**2**) instrument shows that no significant difference exists and this is at a particularly high probability of confidence (i.e. the chance of making a type I error). However, the results for the SSKI ($p = 0.056$) suggest that this degree of confidence is perhaps not as high as that stated by the results from the Al-Turaiki (**2**) instrument. This finding may be important with respect to complex injuries regarding the posterior cruciate ligament and perhaps the medial collateral and lateral collateral ligaments, hence the values of general and mid-range stiffness should also be compared.

5 DISCUSSION

It is evident that the SSKI device demonstrates differences between the two knees and although the instrument applies different levels of displacement and measures different resistive loading it appears to be more sensitive to changes in knee stiffness. This aspect is particularly important when testing patients with severe ligament disruption. In this instance the instrument is able to detect the difference by applying a fixed tibial displacement of 5 mm. In addition, the mean resistive load values produced by the SSKI device (anterior 53 N and posterior 82 N) are less than the applied 120 N from the Al-Turaiki (**2**) instrument. This aspect may be

Table 2 Mean values for instability testing using the Al-Turaiki (**2**) device and the Salford static knee instability instrument (SSKI) on 14 patients with suspected isolated rupture of the ACL of one knee

	Al-Turaiki (**2**) device				Salford static knee instrument (SSKI)		
	Uninjured	Injured	% Difference		Uninjured	Injured	% Difference
Anterior stiffness (N/mm)	19.28	12.35	Decrease 35	Anterior stiffness (N/mm)	9.85	4.23	Decrease 58
Posterior stiffness (N/mm)	24.96	23.71	Decrease 6	Posterior stiffness (N/mm)	15.72	14.63	Decrease 7
Anterior laxity (mm)	5.91	8.42	Increase 30	Anterior load (N)	53	28	Decrease 48
Posterior laxity (mm)	3.7	4.2	Increase 11	Posterior load (N)	82	64	Decrease 22
Total laxity (mm)	9.61	12.62	Increase 23	Total load (N)	135	92	Decrease 31

Table 3 Statistical difference testing between uninjured and injured limbs of 14 subjects on the Al-Turaiki (**2**) device and Salford static knee instability instrument (SSKI) (Bonferonni alpha correction for significance, $p = 0.0125$)

Variables	Test of significance	Difference mean	Standard deviation	Standard error	Correlation	*t*-value	Two tail probability
Al-Turaiki (**2**) device							
Anterior stiffness	Paired *t*-test	6.92	6.67	1.78	0.156	3.88	0.002*
Posterior stiffness	Paired *t*-test	1.25	7.11	1.901	0.382	0.30	0.768
Relative difference (anterior–posterior stiffness)	Paired *t*-test	−0.358	0.377	0.101	−0.113	−3.56	0.003*
SSKI							
Anterior stiffness	Paired *t*-test	5.62	2.98	0.98	−0.020	6.74	0.000*
Posterior stiffness	Paired *t*-test	1.09	2.65	0.69	0.594	2.76	0.056
Relative difference (anterior–posterior stiffness)	Paired *t*-test	−0.50	0.192	0.051	0.436	−9.84	0.000*

* Indicates significance.

particularly important regarding patients with severe joint disruption when the lower load values would not cause severe discomfort to the patient. It seems therefore, that the SSKI device applies similar tibial displacement values (anterior 5 mm and posterior 5 mm) to those measured by the Al-Turaiki (**2**) device (anterior 5.91 mm and posterior 3.70 mm when measured in this pathological group), but produces a larger difference in the stiffness and laxity/load variables between the two knees.

In conclusion, it should be noted that the two instruments are actually demonstrating the same tendency within results for the group of patients with suspected ACL rupture of one knee. It also seems that the relative difference values [(uninjured value − injured value)/uninjured value] in anterior and posterior stiffness are good indicators for joint deficiency and should be utilized more often in quantitative knee joint assessment. Furthermore, it is suggested that for complete diagnostic value the measures of general and mid-range stiffness should also be examined as they appear to be good indicators for secondary restraining structures.

The SSKI apparatus produced results which in an overall examination were similar to those for the Al-Turaiki (**2**) device. However, the difference between the measured variables for the two knees was greater on the SSKI device than on the Al-Turaiki (**2**) instrument. It is suggested therefore that the technique of applied displacement and measurement of resistive load is more sensitive than the conventionally used technique of applied load and measured displacement. Furthermore, this difference in sensitivity between the two devices and the non-linear relationship of the knee are important clinical concepts that may justify further research and examination.

6 CONCLUSIONS

The SSKI device and the Al-Turaiki (**2**) instrument produced results that confirmed the clinical assessment of isolated rupture of the ACL of one knee.

The SSKI device and the Al-Turaiki (**2**) instrument produced results for posterior stiffness in the two knees which were conflicting and confusing. The degree of statistical difference between the uninjured and injured knees on the SSKI device showed results that were different to the Al-Turaiki (**2**) instrument [SSKI device ($p = 0.056$), Al-Turaiki (**2**) device ($p = 0.768$)].

The SSKI device and the Al-Turaiki (**2**) device showed that the pathological knee joint with suspected isolated rupture of the ACL of one knee did not function in a linear manner where measurements of stiffness, laxity and resistive load were concerned.

Both devices showed the measurement of relative difference in stiffness (over both knees and between anterior and posterior) may be the most useful clinical diagnostic measurement for assessment of isolated or complex ligamentous injury cases [SSKI device ($p = 0.000$) and Al-Turaiki (**2**) device ($p = 0.003$)].

It is believed that the technique proposed by Butler *et al.* (**1**) is more sensitive to clinical change in an injured knee than the conventional method of applied load and measurement of displacement or laxity.

Finally, it could be suggested that the difference observed between the two techniques could be attributed to the fact that the SSKI device potentially can be instrumented more accurately from an engineering perspective, than with the case of the Al-Turaiki (**2**) device. It is therefore stated that the SSKI is more sensitive to the changes which occur between the two knees following ligament injury. For this reason the SSKI was utilized for the continuing clinical service offered by the department.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Phillip Turner, Consultant Orthopaedic Surgeon and the Science and Engineering Research Council of the United Kingdom (currently the Engineering and Physical Sciences Research Council) for financial support.

REFERENCES

1 **Butler, D. L., Noyes, F. R.** and **Grood, E. S.** Ligamentous restraints to anterior–posterior drawer in the human knee. *J. Bone Jt Surg*., 1980, **62-A**(2), 259–270.

2 **Al-Turaiki, M. H. S.** A non-invasive quantitative assessment of human knee joint instability *in-vivo*. PhD thesis, Department of Orthopaedic Mechanics, University of Salford, England, 1984.

3 **Brantigan, D. C.** and **Voshell, A. F.** The mechanics of the ligaments and menisci of the knee joint. *J. Bone Jt Surg*., January 1941, **XXIII**(1), 44–66.

4 **Fukubayashi, T., Torzilli, P. A., Sherman, M. F.** and **Warren, R. E.** An *in-vitro* biomechanical evaluation of anterior–posterior motion of the knee. *J. Bone Jt Surg*., 1982, **64-A**, 258–264.

5 **Gollehon, D. L., Torzilli, P. A.** and **Warren, R. F.** The role of the posterolateral and cruciate ligaments in the stability of the human knee: a biomechanical study. *J. Bone Jt Surg*., 1987, **69-A**(2), 233–242.

6 **Lipke, J. M., Janecki, C. J., Nelson, C. C., Mcleod, P., Thompson, C., Thompson, J.** and **Haynes, D. W.** The role of incompetence of anterior cruciate and lateral ligaments in the antero-lateral and antero-medial instability. *J. Bone Jt Surg*., 1981, **63-A**, 954–960.

7 **Piziali, R. L., Seering, W. P., Nagel, D. A.** and **Schurman, D. J.** The function of the primary ligaments of the knee in anterior–posterior and medial–lateral motions. *J. Biomechanics*, 1980, **13**, 777–784.

8 **Piziali, R. L., Rastegar, J., Nagel, D. A.** and **Schurman, D. J.** The contribution of the cruciate ligaments to the load–displacement characteristics of the human knee joint. *J. Biomech. Engng*, 1980, **102**, 277–283.

9 **Markolf, K. L., Graff-Radford, A.** and **Amstutz, H. C.** *In-vivo* knee stability: a quantitative assessment using an instrumented clinical testing apparatus. *J. Bone Jt Surg*., 1978, **60-A**(5), 664–674.

10 **Daniel, D. M., Malcolm, L. L., Losse, G., Stone, M. L., Sachs, R.** and **Burks, R.** Instrumented measurement of anterior laxity of the knee. *J. Bone Jt Surg*., 1985, **67-A**(5), 720–726.

11 **Hanten, W. P.** and **Pace, M. B.** Reliability of measuring anterior laxity of the knee joint using a knee ligament arthrometer. *Phys. Therapy*, 1987, **67**(3), 357–359.

12 **Dahlkvist, N. J.** Objective evaluation of knee stability with particular reference to ligamentous and meniscal injuries. PhD thesis, Rheumatology and Rehabilitation Unit, School of Medicine, University of Leeds, England, 1986.

13 **Shinno, K., Inoue, M., Horibe, S., Nakamura, H.** and **Ono, K.** Measurement of anterior instability of the knee: a new apparatus of clinical testing. *J. Bone Jt Surg*., 1987, **69-B**(4), 608–613.

14 **Markolf, K. L., Kochan, A.** and **Amstutz, H. C.** Measurement of knee stiffness and laxity in patients with documented absence of the ACL. *J. Bone Jt Surg*., 1984, **66-A**(2), 242–252.

15 **Shoemaker, S. C.** and **Markolf, K. L.** *In-vivo* rotatory knee stability: ligamentous and muscular contributions. *J. Bone Jt Surg*., 1982, **64-A**(2), 208–216.