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An objective tool for assessing the outcome of total knee replacement surgery

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Abstract: The need for an objective tool to assess the outcome of total knee replacement (TKR) surgery is widely recognized. This study investigates the potential of an objective diagnostic tool for assessing the outcome of TKR surgery based on motion analysis techniques. The diagnostic tool has two main elements: collection of data using motion analysis, and the assessment of knee function using a classifier that is based around the Dempster–Shafer theory of evidence. The tool was used to analyse the knee function of nine TKR subjects pre-operatively and at three stages post-operatively. Using important measurable characteristics of the knee, the tool was able to establish the level of benefit achieved by surgery and to enable a comparison of subjects. No subject recovered normal knee function following TKR surgery. This has important implications for knee implant designs.

Keywords: classification, Dempster–Shafer theory, gait analysis, knee function, outcome measure, total knee replacement

1 INTRODUCTION

Total knee replacement (TKR) surgery is used to treat approximately 35 000 patients with knee osteoarthritis (OA) in the UK each year [**1**]. The procedure is performed primarily to reduce the pain associated with the degenerative disease and to restore a degree of normal knee function [**2**, **3**]. The beneficial implications of a return towards normal function include better mobility and an improved functional effect on other lower limb joints by removing the need for compensatory gait mechanisms. Additionally, for congruent mobile bearing knees, a return to normal function can result in a decrease in the contact and shear stresses on the articulating surfaces of the replacement joint, thus reducing polyethylene wear and subsequent implant failure.

The need for an objective tool to assess the outcome of TKR surgery is widely recognized. In response to this need, there has been an emergence of two types of system to assess knee function before and after TKR surgery: the patient-reported scoring systems and motion analysis studies. In general, patient-reported scoring systems attempt to measure patient well-being in terms of pain and daily life activities. Examples of such systems are The Knee Outcome Survey (KOS) [**4**], The Western Ontario and McMaster Universities (WOMAC) Osteoarthritis Index (see reference [**5**]), the Oxford Knee System (see reference [**5**]). However, they do not offer an objective assessment of the function of the knee. In contrast, motion analysis studies can provide an objective measure of knee function (see, for example, references [**2**], [**3**], and [**6**] to [**10**]). However, while the field of motion analysis has much to contribute to the development of new and emerging medical diagnostic techniques, there are a number of problems associated with using this approach to obtain an objective measurement of knee improvement.

First, during assessments in motion analysis laboratories, although it is a great advantage that a wealth of biomechanical data relating to knee function can be collected, it is extremely difficult to analyse and gain conclusions objectively from such vast data collections. Second, despite collecting such a mass of data during sessions in the motion analysis laboratory, many studies restrict their analyses to a

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single variable (see, for example, references [**11**] and [**12**]). Among all the variables collected during a typical motion analysis, no individual variable is capable of providing a complete description of a subject's motion [**13**]. Use of one variable, in isolation from the rest, means that a vast amount of potentially important information lies redundant. Rather than identify the changes in individual variables, it would be of value to see how the alteration of multiple variables has combined to produce an overall transformation in a subject's pattern of motion. Third, a high proportion of the data recorded during the motion analysis sessions exists in the form of temporal waveforms. In many studies these temporal waveforms are parameterized [**10–12**, **14**]. A danger associated with this practice is that valuable temporal information is discarded. Furthermore, motion parameters defined using normal temporal waveforms are not always easily identifiable in pathological waveforms [**15–17**].

In response to the problems described, an objective tool was developed that is capable of producing an automated analysis from motion analysis data in terms of classifying OA knee function and quantifying TKR recovery [**18–20**]. This objective tool could be of significant value providing useful information on preoperative disease progression, on the effectiveness of surgical and therapeutic intervention, and on the functional analysis of a range of joint prosthesis designs. With an improvement to the clinical assessment process for common diseases, surgery to relieve the painful and functionally disabling symptoms could be more effectively tailored to suit patients. With sound validation it is possible that the tool could provide a powerful prediction of the extent to which a subject presenting a distinct set of pre-operative symptoms would respond to various treatment options. This study investigates the potential of this objective diagnostic tool for assessing the outcome of TKR surgery based on motion analysis techniques.

2 METHODS

The diagnostic tool has two main elements: collection of data using motion analysis, and the assessment of knee function using a classifier that is based around the Dempster–Shafer theory (DST) of evidence.

2.1 Collection of data using motion analysis

The protocol of Holt *et al.* [**21**] was used to analyse the knee function of a total of 51 subjects, including 20 patients with knee OA, 22 subjects with healthy knee function and no previous injury, pain or diagnosis of knee OA, and nine TKR patients who were analysed at 3, 6, and 12 months post-operatively. Knee rotations, ground reaction forces (GRF), and time–distance parameters were recorded during level walking and anthropometrical measurements were collected. At the end of their visit, subjects completed The Activities of Daily Living Scale of the KOS [**4**].

Following Deluzio *et al.* [**16**] the temporal GRF and knee rotation waveforms were processed using principal component (PC) analysis. Thus each waveform is represented by a predefined number of PC scores which relate to the waveform during specific portions of the gait cycle. This means that temporal information is retained. For interpretation of the PC scores the reader is directed to Jones reference [**18**].

A total of 18 variables were chosen to represent a subject's knee function as shown in Table 1. These include four anthropometrical measurements, two time–distance parameters and 12 PC scores (six related to the GRF waveforms and six related to the knee rotation waveforms).

Both knees were analysed during data collection; however, patients who are affected by advanced knee OA and who require a TKR may unfortunately be affected by the disease in the non-operative knee, even when undiagnosed, and, as such, the functional gait characteristics may be affected by both knees. The current study concentrates on operative knee function, as it is assessing the TKR for that particular knee, with cadence and stance phase included to reflect the whole gait function and with body mass index, knee width, and thigh girth to reflect the effects of (reduced) loading through the knee, inflammation and bruising due to the disease and the surgical procedure, and the muscle mass as an indicator of muscle weakness and wastage respectively.

The body mass index reflects the forces acting through the knee and is thus important in terms of load acceptance and thus off-loading the knee when it is painful or unstable both pre- and post-operatively. Knee swelling as indicated by the knee width indicates inflammation at the joint, possibly due to the disease whether in the knee joint between the articulating surfaces or in the soft tissue that supports the knee during its function. It also reflects tissue repair as it changes over the 12 month post-operative period as the knee soft-tissues and implant–bone interfaces repair and recover. This is an important factor in determining knee function as

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Table 1 List of the variables v_i ($i = 1$ to 18) used in the classification process

Variable v_i	Variable description	Interpretation
v_1	Body mass index (kg/m^2)	Indicator of loading through the knee
v_2	Cadence (min^{-1})	Indicator of ability to walk with a normal gait
v_3	Stance phase (per cent of the gait cycle)	Indicator of ability to load knee during gait
v_4	PC score 1	Difference between the peak anterior GRF and the peak posterior GRF
v_5	PC score 2	Magnitude of the anterior–posterior GRF during the period from late midstance to midterminal stance
v_6	PC score 3	Magnitude of the anterior–posterior GRF during late pre-swing
v_7	PC score 4	Magnitude of the vertical GRF during a portion of midstance and the period from heel rise to opposite initial contact
v_8	PC score 5	Magnitude of the vertical GRF from loading response to mid-stance
v_9	PC score 6	Magnitude of the vertical GRF during the phase from heel strike transient to the first peak vertical GRF
v_{10}	PC score 7	Magnitude of knee flexion from initial contact to opposite initial contact
v_{11}	PC score 8	Magnitude of knee flexion during the phase from 58 per cent to 76 per cent of the gait cycle
v_{12}	PC score 9	Magnitude of knee abduction–adduction during the stance phase
v_{13}	PC score 10	Magnitude of knee abduction–adduction during the initial swing
v_{14}	PC score 11	Magnitude of knee abduction–adduction during the terminal swing
v_{15}	PC score 12	Magnitude of internal–external rotation from the loading response to the mid swing
v_{16}	Mediolateral knee width (mm)	Indicator of knee swelling
v_{17}	Anterior–posterior knee width (mm)	Indicator of knee swelling
v_{18}	Thigh girth (mm)	Indicator of muscle mass

it affects the knee stability and ability to load-bear, translate, and rotate during gait both pre- and post-operatively. Thigh girth is an indicator of muscle mass, which can be affected my inactivity due to pain and reduced knee function during daily activities pre-operatively, leading to muscle wastage. The extensor muscles play an important role during knee function, such as during walking as they stabilize the knee for load acceptance during the stance phase and in response to external flexion moments. Pre-operative extensor muscle wastage can thus affect knee function and also recovery rates, and the thigh girth measures changes in the muscle mass that occur from the pre- to post-operative stages as the patient's knee recovers stability and they use it with increasing confidence.

2.2 Assessment of knee function using the DST-based classifier

The DST-based classifier enables decision making in the presence of uncertain, inadequate, and conflicting evidence, a common problem in the motion analysis laboratory. The DST-based classifier [**18–20**] transforms a subject's knee function data into a set of exact belief values (BVs): a level of belief that a subject has OA knee function, denoted $m(\{\text{OA}\})$; a level of belief that a subject has normal knee function, denoted $m(\{\text{NL}\})$; an associated level of uncertainty, denoted $m(\Theta)$. These BVs are then represented as a unique point on a simplex plot. In the simplex plot, the least distance from the point to each side of the equilateral triangle is in the same proportion to the three BVs (Fig. 1(a)), i.e. the distances $\text{pe}_1 = hm(\{\text{OA}\})$, $\text{pe}_2 = hm(\{\text{NL}\})$, and $\text{pe}_3 = hm(\Theta)$ (where h is the height of the triangle). It can be seen that, as $m(\{\text{NL}\})$, increases the distance pe_1 also increases. This means that, the nearer the point is to the normal vertex (labelled {NL} in Fig. 1), the greater the level of normal knee function a subject has. Similarly, as $m(\{\text{OA}\})$ increases, the distance pe_2 increases and so, the nearer the point is to the OA vertex (labelled {OA} in Fig. 1), the greater the level of OA knee function a subject has. Consequently, the simplex plot can be divided into four classification regions (Fig. 1(b)), namely dominant normal ($m(\{\text{NL}\}) \geqslant 0.5$) (region A), dominant OA ($m(\{\text{OA}\}) \geqslant 0.5$) (region B), non-dominant normal ($m(\{\text{OA}\}) < m(\{\text{NL}\}) < 0.5$) (region C), and non-dominant OA ($m(\{\text{NL}\}) < m(\{\text{OA}\}) < 0.5$) (region D). Jones [**18**] showed that subjects with knee OA tend to lie within the dominant OA region of the simplex plot and normal subjects within the dominant normal region.

The control parameters of the DST-based classifier were designed using the knee function data of the 20 OA and 22 normal subjects [**18–20**]. The DST-based classifier was then used to assess the knee function of the nine TKR subjects over four visits (pre-operatively (visit 1) and at three stages (3 months (visit 2), 6 months (visit 3), and 12 months (visit 4)) following TKR surgery.

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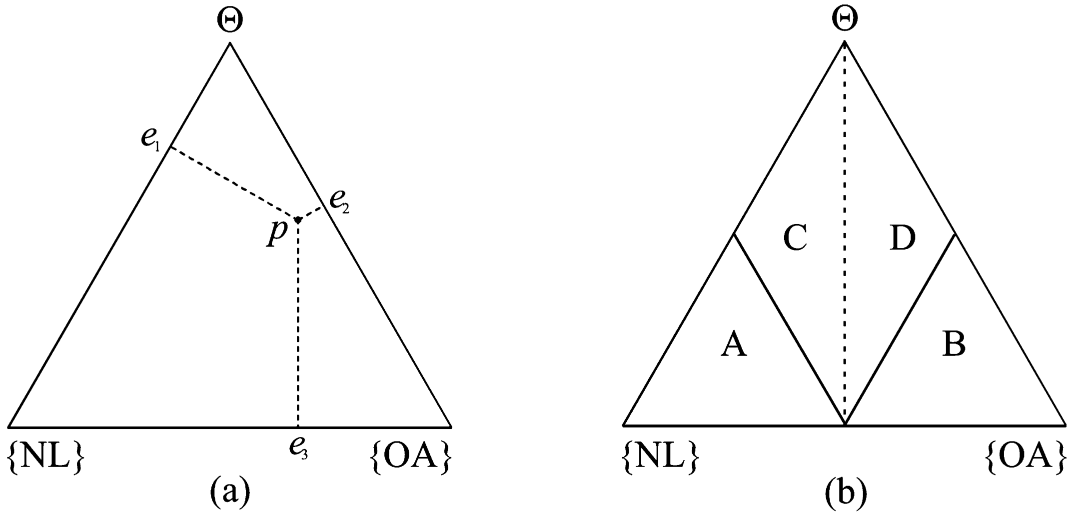

Fig. 1. Simplex plot (a) showing the relationship between the position of a point in the simplex plot and the BVs, where the distances $pe_1 = hm(\{OA\})$, $pe_2 = hm(\{NL\})$, and $pe_3 = hm(\Theta)$ (where h is the height of the triangle) and (b) showing the areas of dominant normal (region A), dominant OA (region B), non-dominant normal (region C), and non-dominant OA (region D) classification

3 RESULTS

The BVs ($m(\{NL\})$) denoting normal knee function for the nine TKR subjects are recorded in Table 2. Comparison of these BVs for each visit enables the level of benefit achieved by surgery to be established. An increase in the normal BV from one visit to the next suggests that a subject has experienced some recovery of normal knee function following TKR surgery. The level of benefit achieved by surgery can also be seen and shown in terms of simplex coordinates in Fig. 2. The results of the classification tool were compared with the results of the KOS [**4**] which are recorded in Table 2. The KOS score is displayed as a percentage, with a high score being associated with a high level of function and vice versa.

4 DISCUSSION

In his paper on rating systems for TKR, Davies [**5**] suggested that such a tool for assessing outcome methods should fulfil the following main requirements.

1. The level of benefit achieved by surgery should be established.
2. It should enable direct comparison between subjects to be made.
3. The outcome should be related the clinical results.
4. It should be simple.
5. Important measurable characteristics of the knee that are clinical variables and are easily quantified should be used.

Table 2 Pre- and post-operative normal BVs $m(\{NL\})$ and KOS scores for the nine TKR subjects (TKR1 to TKR9)

	$m(\{NL\})$				KOS score (%)			
Subject	Visit 1	Visit 2	Visit 3	Visit 4	Visit 1	Visit 2	Visit 3	Visit 4
TKR1	0.1366	0.3163	0.0690	0.1718	25.00	63.50	75.00	73.75
TKR2	0.0111	0.0964	0.1799	0.1582	50.00	55.00	70.00	66.25
TKR3	0.0067	0.0191	0.0486	0.0264	31.25	82.50	58.75	68.75
TKR4	0.0712	0.0955	0.1236	0.1732	28.75	40.00	46.25	56.25
TKR5	0.2200	0.2767	0.3538	0.3554	N/A*	56.25	56.25	73.75
TKR6	0.0561	0.0140	0.2906	0.1014	36.25	55.00	71.25	60.00
TKR7	0.0709	0.0215	0.0338	0.0112	28.75	N/A*	67.50	73.75
TKR8	0.0046	0.0621	0.0971	0.0619	N/A*	67.50	72.50	83.75
TKR9	0.2086	0.1752	0.3933	0.2248	68.75	66.25	80.00	70.00

* N/A, not available.

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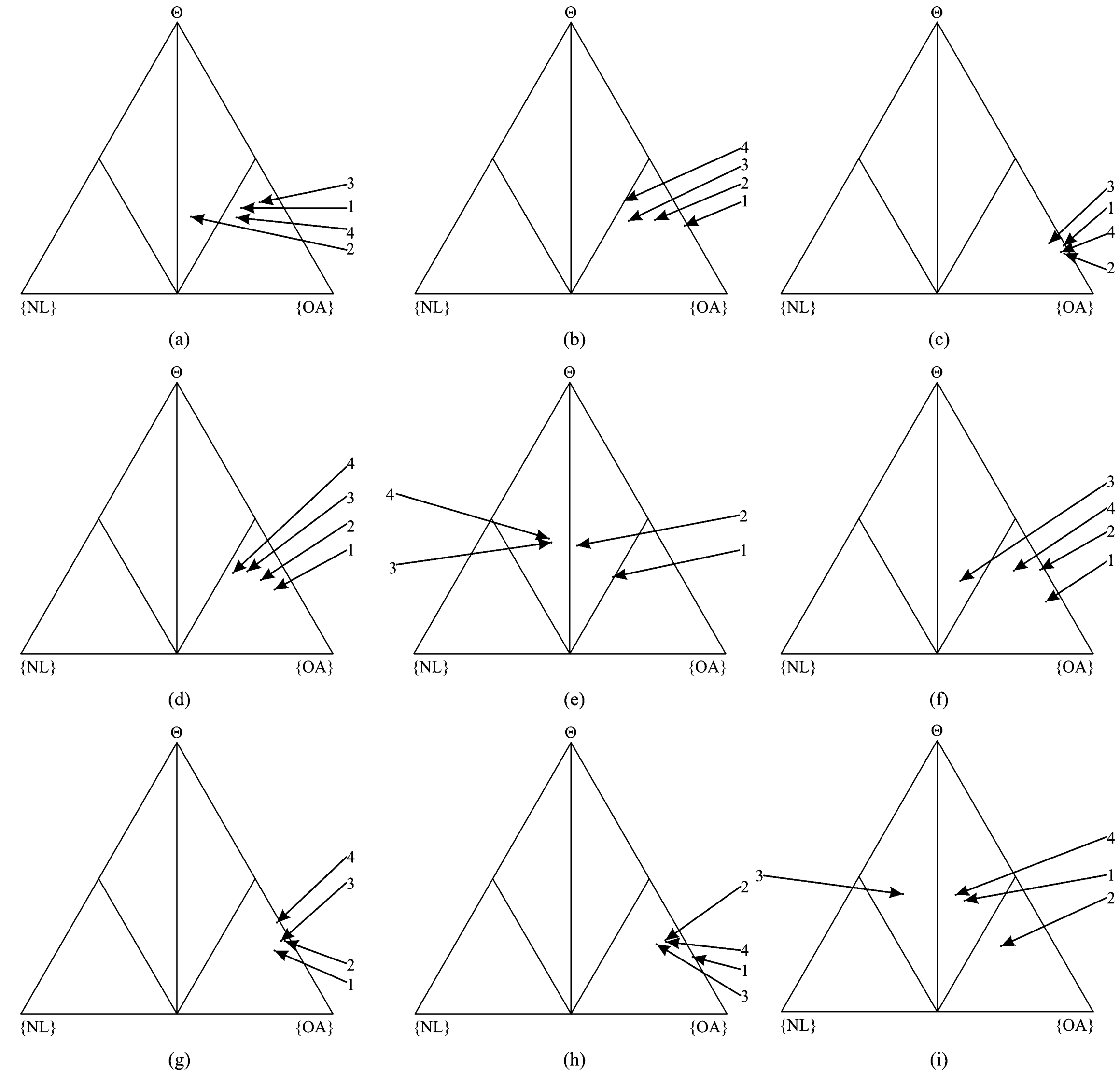

Fig. 2 Simplex plots showing recovery following TKR surgery for the following subjects (a) TKR1; (b) TKR2; (c) TKR3; (d) TKR4; (e) TKR5; (f) TKR6; (g) TKR7; (h) TKR8; (i) TKR9. The numerals indicate the following: 1, pre-operative visit; 2, visit 3 months post-operatively; 4, visit 12 months post-operatively

6. It should enable a direct comparison between different surgical techniques or implants to be made.

The results given in section 3 are now discussed in response to these requirements.

4.1 Level of benefit achieved by surgery

The results have shown that the classification tool enables the level of benefit achieved by surgery to be established. The results have suggested that most of the subjects experienced some degree of recovery of normal knee function as seen in an increase in the $m(\{NL\})$ BVs. However, none of the subjects at any stage of recovery has a normal BV characteristic of a normal subject (i.e. a dominant normal classification of $m(\{NL\}) \geqslant 0.5$, which suggests that none of the subjects recovered complete normal knee function during level walking following TKR surgery. This is in agreement with the work of in references [**2**], [**3**], and [**7**] to [**9**] where it is reported that TKR subjects do not achieve normal knee function over time. This implies that the TKR surgery provides relief from the symptoms associated with OA knee function but that the prosthetic knee does not function in the same way as the normal knee.

During TKR surgery, the articulating surfaces of the tibia, femur, and sometimes the patella are replaced with prosthetic components. Additionally, the anterior cruciate ligament (ACL) and in some cases the posterior cruciate ligament (PCL) are

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sacrificed. Consequently, the normal biomechanics of the knee are altered. In constrained TKR designs, there is an increased congruity of the prosthetic surfaces, which increases the stability of the knee joint and restrains motion. Additionally, in all TKR designs the friction between the metal and plastic surfaces has an effect on the kinematics of the knee [**22**], again resulting in increased knee stability. Removal of the PCL restrains the tibiofemoral roll-back during flexion and consequently reduces the lever arm of the quadriceps. This increases the demand of the quadriceps muscle. However, in subjects who suffer from muscle atrophy, the quadriceps muscle may not be able to provide the additional force needed to extend the knee. In ACL-deficient knees, subjects compensate for no ACL by reducing the demand on the quadriceps, which is seen in a reduction in the flexion–extension moment [**2**]. Many subjects with knee OA adopt compensatory gait mechanisms to reduce the pain experienced during walking. It seems apparent that, over time, these adaptations become habitual. These adaptations and the presence of co-morbidities inevitably affect the subject's ability to walk with a normal pattern of motion. The lack of restoration of normal function following TKR surgery has two main implications. First, there will be a resultant effect on other joints because they have to compensate for the limitations of the replaced knee joint. Second, the abnormal kinematics and consequent increase in the shear forces on the surfaces of the prosthetic joint lead to excessive wear of the prosthetic components and subsequent loosening of the prosthesis. These findings raise the question of whether TKR recovery should be measured in terms of a return to normal knee function or in terms of 'good' TKR function.

4.2 Direct comparison between subjects

The classification tool makes the comparison of different subjects possible. Examination of the BVs and simplex plots shows that, although the TKR subjects have various levels of normal knee function, it is the subjects with the greatest levels of normal knee function before TKR surgery that exhibit the greatest levels of normal knee function after surgery. For example, TKR5 shows the greatest level of normal knee function both pre-operatively and post-operatively.

4.3 Relation of outcome to clinical results

The outcome of the classification tool was compared with the results of a subjective questionnaire, namely the KOS [**4**] (Table 2). No significant correlation was found between the normal BVs, $m(\{NL\})$ and the KOS scores ($r = 0.178$). In the only other study that attempted to relate motion analysis parameters to patient-related scoring systems, Fuchs *et al.* [**8**] found no correlation between the two measures of outcome. The main reason for this inconsistency is that each method provides a different perspective on the assessment of knee function. The diagnostic tool assesses knee function during level walking, whereas the KOS measures knee function during different daily activities and considers clinical parameters such as buckling, instability, and pain. The results raise the question of whether the performance of TKR components should be measured using subjective questionnaires. The correlations across the nine patients are variable and a review of three patients, who could be identified as having a good recovery as determined by the increasing BVs, is given in terms of the comparison with the KOS scores over the four visits from the pre-operative visit through to the post-operative recovery. For TKR1, from the pre-operative to the 3 months post-operative visit, the KOS scores improve from 25 per cent to 63.5 per cent and the BV changes from 0.1366 to 0.3163. From 3 to 6 months the KOS scores improve by a further 11.5 per cent and the BV decreases to 0.069 and from 6 to 12 months the KOS scores increase again to 73.75 per cent and the BV increases to 0.178. The change in BV overall from pre- to post-operative function shows relatively small changes, whereas the KOS scores are increasing. After a strong move towards non-dominant OA for the first 3 months, function is indicated to be closer to OA for the 6-month analysis before returning to a slight relative improvement compared with the pre-operative BV. The KOS scores reflect a reduction in the pain and, as discussed, the fact that the patient may have seen a marked improvement in the ability to perform daily activities and that certain clinical indicators such as swelling, stiffness, and buckling may have been reduced. These factors may improve; however, the knee function may not have returned towards normal to the extent reflected in the KOS score as indicated by the BVs and the correlation is low (0.0273). For TKR5 the BVs reflect an improvement from a relatively high pre-operative $m(\{NL\})$ value of 0.22 placing them on the border between what could be considered as the dominant and non-dominant OA knee function regions of the simplex plot, to increases over the 3, 6, and 12 months of 0.2767 to 0.3538 to 0.3554 respectively. Thus the patient has moved from 3 to 6 months into

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the non-dominant $m(\{NL\})$ region with a similar BV at 12 months. This patient reflects the indication that it is the subjects with the greatest levels of normal knee function before TKR surgery that exhibit the greatest levels of normal knee function after surgery. The KOS scores, although not available for the pre-operative visit, indicate a moderately good outcome of around 56 per cent at 3 and 6 months with an improvement at 12 months to 78 per cent. The patient clearly felt that the knee was improving over the 12 months, as reflected in the increasing KOS scores, owing to recovery from the surgery in terms of daily activity and stability and this is also reflected in the increasing BVs. However, the correlation, although higher than that for TKR1, is still low (0.5153). TKR9 shows a relatively high initial pre-operative BV of 0.2086, which drops to 0.1752 at 3 months for the post-operative visit and then increases to a value above the initial value (0.3933), moving them into the non-dominant $m(\{NL\})$ region of the simplex plot. However, at 12 months, the BV falls to 0.2248, which moves them back towards that found for the pre-operative visit and into the non-dominant OA knee function region. The KOS scores reflect this in some way as they fall from 68.75 per cent to 66.25 per cent from pre- to the first post-operative visit at 3 months, which can be though to be interpreted as a poor outcome even for the 3 month visit when the patients should be scoring to reflect a reduction in pain. However, the KOS scores mirror the BVs, increasing from 3 to 6 months to 80 per cent and then falling back to 70 per cent at 12 months; thus for this patient, the correlation is high ($r = 0.9989$).

4.4 Simplicity of the diagnostic tool

The diagnostic tool is simple and logical and the progression from taking clinically relevant measurements to making a decision using the simplex plot can be clearly followed. This has become evident when communicating the method and results across a wide spectrum of disciplines as the method has been well received by engineers, mathematicians, physiotherapists, and orthopaedic surgeons [**19**, **20**, **23**, **24**].

4.5 Use of clinically relevant and easily quantifiable varibles

The tool must be accurate and clinically relevant with due consideration of errors. The results of a previous study [**20**], where the performance of the DST classifier, in terms of accuracy and ambiguity, was compared with a method that is well established and has been used as a benchmark in other comparative studies, namely linear discriminant analysis (LDA), reveal that the DST method is a highly accurate classification tool. It was able to classify new subjects with an accuracy superior to that of a well-established method, LDA. A possible source of large measurement errors must be considered when measuring the out-of-sagittal plane rotations and, in particular, the internal–external knee rotations. Currently, the inputs to the classifier may be representative of relatively large errors combined with actual knee rotations as the present authors are following a standard retroreflective marker-based approach to the data collection and analysis using Qualisys (Sweden) motion capture cameras and tracking software. Thus the derivations of the knee range of motion can be largely affected by errors associated with the skin motion artefact that commonly occur during subject data collection.

4.6 Direct comparison between different surgical implants or techniques

The method thus requires further thought, development, and validation before it can be implemented. Further work must be undertaken to ensure that the tool meets the further requirements of Davies [**5**]. It is anticipated that the tool can be used to compare outcomes from different surgical techniques or implants, although this prospect is beyond the scope of the current study. It is proposed to use the method to study the differences between rotating-platform and fixed-bearing knee implants.

5 CONCLUSIONS

The initial results of this application have demonstrated an approach that can be used to identify the extent to which a subject has recovered after TKR surgery. The DST-based classification tool is simple, logical, and visual, and the progression from taking clinically relevant measurements to making a decision using the simplex plot can be clearly followed. It is anticipated that the tool can be used to compare outcomes from different surgical techniques or implants. If this new tool is to provide an enhancement to diagnosis, orthopaedic intervention, and rehabilitation, it will require confident use by orthopaedic surgeons, therapists, and biomechanical engineers collectively. Consequently, further

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work is required to ensure that the objective DST-based classifier is an effective tool that provides an enhancement to subjective clinical opinion. This will be achieved through extension of the number of TKR subjects, investigation of the accuracy of the motion analysis technique using fluoroscopy, and collaboration with orthopaedic surgeons.

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APPENDIX

Notation

h	height of triangle
$m(\{NL\})$	level of exact belief that a subject has normal knee function
$m(\{OA\})$	level of exact belief that a subject has osteoarthritis knee function
$m(\Theta)$	level of uncertainty
r	correlation coefficient

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