Acta of Bioengineering and Biomechanics
Vol. 16, No. 2, 2014

Original paper
DOI: 10.5277/abb140209

Application of an artificial neural network and morphing techniques in the redesign of dysplastic trochlea

KYUNG JIN CHO[1], JACOBUS H. MÜLLER[1]*, PIETER J. ERASMUS[2], DAVID DEJOUR[3], CORNIE SCHEFFER[1]

[1] Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Stellenbosch, South Africa.
[2] Department of Orthopaedics, Stellenbosch University, Tygerberg, South Africa.
[3] Department of Knee and Sport Surgery, Lyon Ortho Clinic, Lyon, France.

Segmentation and computer assisted design tools have the potential to test the validity of simulated surgical procedures, e.g., trochleoplasty. A repeatable measurement method for three dimensional femur models that enables quantification of knee parameters of the distal femur is presented. Fifteen healthy knees are analysed using the method to provide a training set for an artificial neural network. The aim is to use this artificial neural network for the prediction of parameter values that describe the shape of a normal trochlear groove geometry. This is achieved by feeding the artificial neural network with the unaffected parameters of a dysplastic knee. Four dysplastic knees (Type A through D) are virtually redesigned by way of morphing the groove geometries based on the suggested shape from the artificial neural network. Each of the four resulting shapes is analysed and compared to its initial dysplastic shape in terms of three anteroposterior dimensions: lateral, central and medial. For the four knees the trochlear depth is increased, the ventral trochlear prominence reduced and the sulcus angle corrected to within published normal ranges. The results show a lateral facet elevation inadequate, with a sulcus deepening or a depression trochleoplasty more beneficial to correct trochlear dysplasia.

Key words: *artificial neural network, trochlea redesign, trochlear dysplasia, trochleoplasty, trochlea morphing*

1. Introduction

Patella stability is largely dependent on the trochlear groove geometry [1]–[4]. An abnormally shaped trochlea, e.g., a dysplastic trochlea, is associated with patella instability and patella dislocation [5]–[7], and the patella's mediolateral behaviour (shift and tilt) under weight-bearing conditions has a strong correlation to the three dimensional geometry of the trochlea [8]. There are different surgical procedures available to restore stability if conservative techniques are unsuccessful; these include surgical modification of the geometry (e.g., trochleoplasty); medial soft tissue anatomy restoration (e.g., medial patellofemoral ligament (MPFL) reconstruction); or bone realignment (e.g., tibial tubercle osteotomy). Any combination of the procedures mentioned can be used. Modification of the trochlear geometry is however challenging since there are few guidelines on what modifications to the geometry will be beneficial.

In this study, we present a method by which a normal trochlea geometry can be predicted based on the unaffected femoral knee parameters. We employ a trained artificial neural network that has

---

* Corresponding author: J.H. Müller, Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Stellenbosch, 7602, South Africa. Tel: +27 21 808 4074, fax: +27 86 645 5206, e-mail: cobusmul@sun.ac.za

Received: July 23rd, 2013
Accepted for publication: October 14th, 2013

the capacity to predict normal values for abnormal dysplastic trochlea parameters as a function of the normal unaffected parameters. This enables redesigning of the dysplastic trochlear groove by using the predicted parameters as a guideline for the normal geometry.

The trochlea is oriented medially in the proximal half of the groove and laterally in the distal half with reference to the femoral mechanical axis [9], whereas when viewed in the sagittal plane (parallel to the femoral mechanical axis) it has a circular appearance [10]. In the latter study [10], spheres were fitted to the lateral and the medial femoral condyles, and defined the line joining the sphere centres as the axis of flexion. This axis also contains the centre point of the arc that encompasses the circular geometry of the trochlear groove centre line. We hypothesise that this relationship can be exploited to predict the trochlear groove geometry by a series of sagittal arcs if the axis containing the centre points can be reliably identified.

Segmentation techniques have been shown to provide three dimensional models from which accurate measurements can be obtained [11]. We employ a standardised measurement framework in which femoral parameter values are extracted from the segmented three dimensional models of normal femurs. Sagittal slices that span the width of the trochlear groove are created and two curve fitting algorithms are compared to quantify the groove curvature. A plane is defined by three parameters (a translation vector from the distal condylar plane and two orientations with respect to the abduction-adduction and flexion-extension axes) that contains the trochlear groove arc centre points. These three parameters (plane parameters) in conjunction with the trochlear depth, sulcus angle, anterior-posterior (AP) dimensions (medial, central and lateral), lateral tilt inclination (LTI), trochlear facet asymmetry ratio, and mediolateral dimension serve as input to an artificial neural network: called a Self-Organising Map (SOM) [12]. It enables the identification of the hidden relationship between high dimensional data, by mapping it onto a regular low-dimensional grid.

A database with parameter sets of healthy knees was created to serve as training material for the SOM. It was then used as a tool to predict normal parameter values for parameters affected by the dysplasia based on the unaffected parameters of four dysplastic knees (Type A, B C and D classified according to the method proposed by Dejour et al. (1998) [13]). The three dimensional models of the dysplastic trochlea were then morphed using the predicted normal values as guidelines. This enabled us to qualitatively access and visualise the modifications that would be needed to correct the dysplasia surgically, i.e., what modification based on the type of trochlea dysplasia will be most suitable for the specific type of dysplasia.

2. Materials and methods

2.1. Study population

With ethical consent from the Committee for Human Research at Stellenbosch University (project number N08/02/029) in accordance with the Declaration of Helsinki, 10 right and 5 left knees from nine volunteers (6 female and 3 male) with a mean age of 37 years (SD = 8.2) were imaged with a computed tomography (CT) scanner (using a Siemens Emotion 16; 130 kV) after obtaining informed consent. The average height of the volunteers is 165.4 cm (SD = 5.29 cm) and an average mass of 70.1 kg (SD = 11.5). None of the volunteers complained of knee pain nor had any prior surgery performed on their knees. The scans were examined by three experienced orthopaedic surgeons, and no sign of trochlear dysplasia was found. Four additional knees were identified for this study, each presenting with trochlear dysplasia in one of the four classes [13]:

- Dysplasia Type A:
  - Gender: female
  - Age: 19 years
- Dysplasia Type B:
  - Gender: female
  - Age: 37 years
- Dysplasia Type C:
  - Gender: female
  - Age: 27 years
- Dysplasia Type D:
  - Gender: male
  - Age: 21 years

Segmentation techniques are employed to generate three dimensional models of the femurs. These include the femoral head, shaft and the condyles. A semi-automated segmentation approach is used: Thresholding is applied to generate a preliminary mask that contained the femoral part of the CT scan. This provides a general three dimensional model of the femur. Improvements are made afterwards, by filling voids and removing artefacts resulting from noise with similar Hounsfield numbers to that of the skeletal bone in the CT scan. Finally, the three dimensional models are smoothed by employing software algorithms (Mimics 14.11, Materialise, Leuven, Belgium).

2.2. Measurement framework

The measurement framework was established and implemented in 3Matic (3Matic 6.0, Materialise, Leuven, Belgium). The femoral mechanical axis is approximated by a line joining the femoral head centre and the distal protrusion point of the anatomical axis. A sphere fitted on the femoral head provides the femoral head centre whereas the axis of a cylinder fitted to the femoral shaft provides the anatomical axis. Next, the posterior condylar plane is defined to be coincident on the posterior condylar line and to be parallel to the mechanical axis in the sagittal view. The distal condylar plane encompasses the most distal points on the medial and lateral condyles and is perpendicular to the posterior condylar plane. The origin for the measurement coordinate system is defined as the point furthest from the distal condylar plane on the trochlea distal border. The abduction-adduction axis (*X*-axis) is defined to be perpendicular to the posterior condylar plane; the internal-external rotation axis (*Y*-axis) is defined to be parallel to the mechanical axis; the extension-flexion axis (*Z*-axis) is defined by the vector resulting from the cross-product of the *X* and *Y* axes unit vectors (Fig. 1).

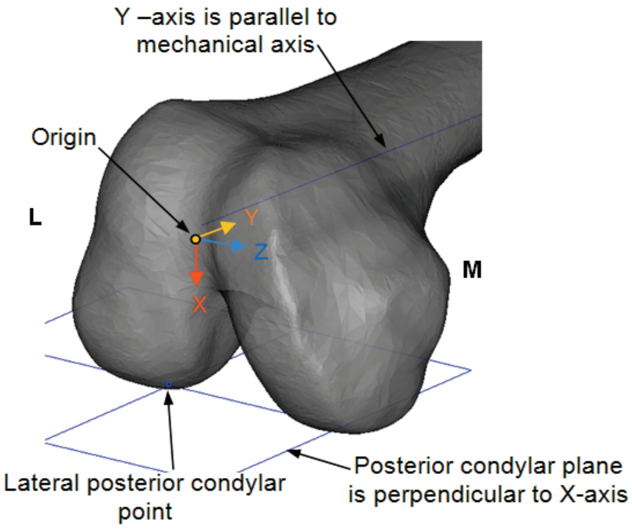

Fig. 1. Coordinate system on a three-dimensional model

2.3. Clinical parameters

A reproducible measurement plane is defined on which all the clinical parameters are measured (Fig. 2). It is coincident with the lateral posterior condylar point and is parallel to the distal plane. The trochlear depth (TD), sulcus angle, lateral tilt inclination (LTI) and trochlear facet asymmetry ratio are measured on the measurement plane (Fig. 3). The medial-lateral (ML) distance is defined as the distance between the most medial and most lateral points of the distal femur, measuring parallel to the distal and measurement plane. The ventral trochlear prominence (VTP) is measured on a sagittal slice (mechanical middle plane) parallel to the mechanical axis coincident on the measurement framework origin (Fig. 4).

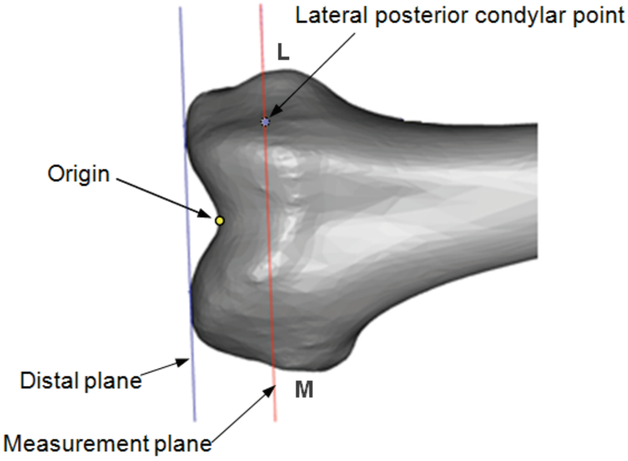

Fig. 2. Measurement framework

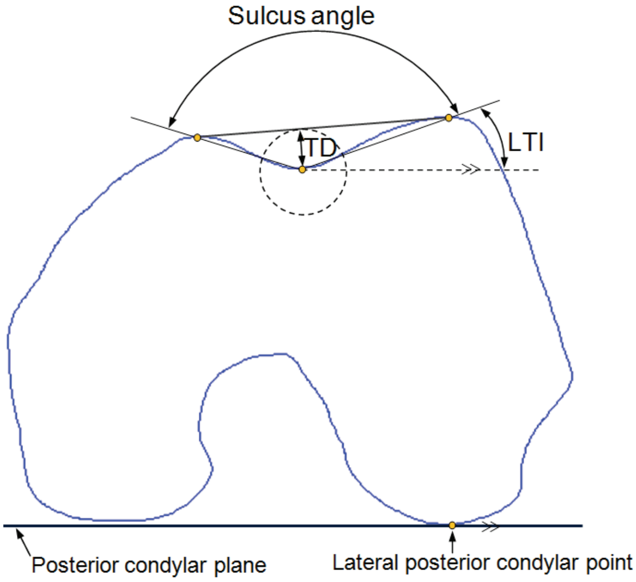

Fig. 3. Femoral parameters measurement on the measurement plane

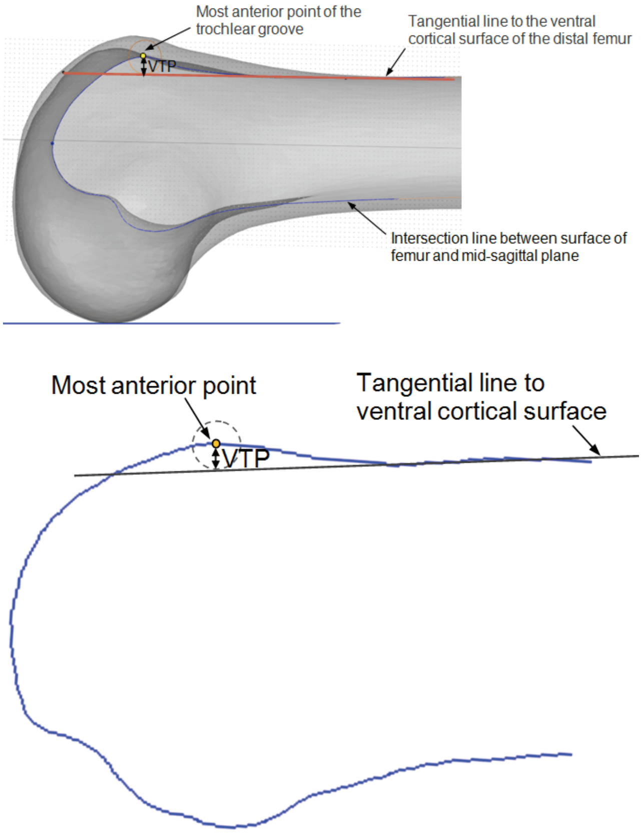

Fig. 4. Ventral trochlear prominence (VTP) measurement on the mechanical middle plane

2.4. Curve generation and analysis

In order to test the hypothesis that a plane containing centre points of arcs on the trochlear groove geometry can be obtained, the mechanical middle plane is used as a reference from which additional sagittal planes are generated. Four medial and four lateral planes are created by sequentially moving the mechanical middle plane 3 mm medially and laterally (Fig. 5). Four medial slices with 3 mm thickness cover the medial trochlear groove up to the medial peak of the trochlea. The lateral trochlea is wider, and four 3 mm slices do not fully assess the lateral side, but the lateral trochlear height is still incorporated into the prediction with lateral AP height dimension.

For each plane, the circular portion of the articular surface of the trochlea groove is determined by plotting the centres of the curves obtained through the least squares theorem and B-splines methods. Arcs are fitted to the trochlear border in each slice by applying the least squares theorem ($\mathrm{Arc}_{\mathrm{LS}}$). The maximum tolerance between the arc and the data points is set to be 0.5 mm. The B-spline ($\mathrm{Arc}_{\mathrm{BS}}$) method is also employed to generate a distribution of centres of the curvatures for each slice (employing a previously described method [14]). Five control points are used with a maximum tolerance between the data points and the B-splines of 0.3 mm. The distance between the adjacent points on the B-splines curve is set to 0.1 mm. This provided a series of centre points through the slices: one series for the $\mathrm{Arc}_{\mathrm{LS}}$ (nine points) and one series for the $\mathrm{Arc}_{\mathrm{BS}}$ (9 sets of moving centres of the curvature). The arcs are fitted from the most anterior point of the curve and the distal data points are removed until the distribution of the centres obtained from $\mathrm{Arc}_{\mathrm{BS}}$ located closely to the $\mathrm{Arc}_{\mathrm{LS}}$ (Fig. 6).

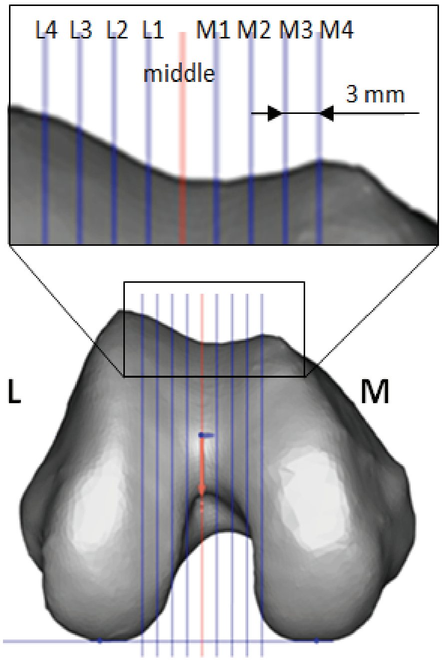

Fig. 5. Sagittal slice plane generation

A plane that is coincident with the nine centre points obtained from $\mathrm{Arc}_{\mathrm{LS}}$ within a 1 mm tolerance can be generated. This is the first important finding to prove our hypothesis that the trochlear groove geometry can be predicted by a series of sagittal arcs if the axis containing the centre points can be reliably identified. However, instead of an axis containing the arc centre points, a plane is identified which contains the centre points. Therefore, if one can reliably predict the location and orientation of the plane, it may still be possible to predict the radii of the arcs and therefore the groove geometry. The position of the centre plane is described by measuring rotation around the flexion-extension axis and internal-external rotation axis and the proximal-distal dimension from the measurement framework origin.

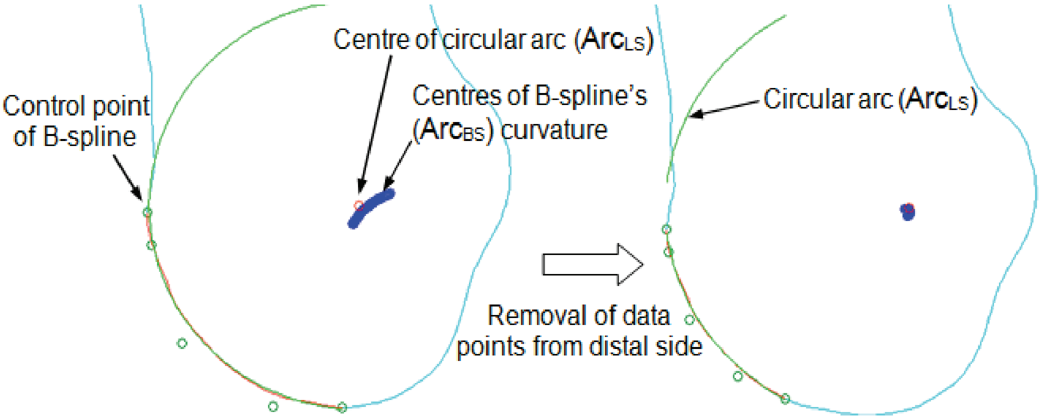

Fig. 6. Sagittal curve fitting on a medial slice (M2)

2.5. An artificial neural network: Self-Organizing Maps

The SOM toolbox developed for Matlab (Mathworks, Natick, United States of America) is used to train the artificial neural network with the data from the normal knees. The trained artificial neural network can be used to estimate the unknown values in a dataset by matching the known parameters with the best matching unit (BMU). Therefore, it may be possible to estimate normal values for dysplasia dependent parameters based on the values of the dysplasia independent parameters of the abnormal knee.

The network was trained with 28 variable sets from 15 normal knees. The known parameters were

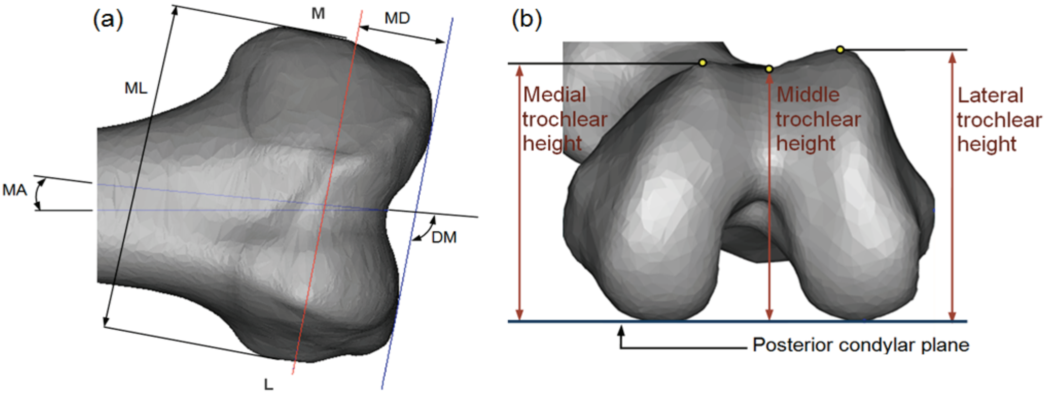

Fig. 7. (a) Trochlear dysplasia independent parameters, (b) trochlear heights

Table 1. SOM input and output parameters

Input	Output
Mediolateral dimension (ML, Fig. 7a)	Arc centres plane: Proximal-distal translation from the distal plane.
Distal condylar plane–measurement plane distance (MD, Fig. 7a)	Arc centres plane: Internal-external rotation among the mechanical axis.
Mechanical axis–anatomical axis angle in the coronal plane (MA, Figure 7a)	Arc centres plane: Flexion-extension among coronal axis to mechanical axis and parallel to the distal plane.
Angle between the distal and mechanical planes (DM, Fig. 7a)	Medial AP dimension (Fig. 7b)
	Central AP dimension (Fig. 7b)
	Lateral AP dimension (Fig. 7b)
	Nine radii of the circular arcs (Fig. 6)
	Nine AP dimensions of the nine slices

defined by two spatial parameters: mediolateral (ML) dimension, and the distance from the distal condylar plane to the measurement plane (MD); and two attitude parameters: the coronal angle difference between the mechanical and anatomical axes (MA), and the angle between the distal and mechanical planes (DM). These parameters are unaffected by trochlear dysplasia (Fig. 7a). The location of the plane containing the arc centres (described by the flexion extension; internal-external rotation and proximal translation), the trochlear heights measured from the posterior condylar planes (medial, central and lateral) (Fig. 7b), and the radius of the circular arcs and the AP dimension for each of the nine slices are estimated by the artificial neural network, Table 1.

The optimal grid size of the SOM is determined to minimise the error of the predicted BMU: 14 samples are used to train the data, after which the 15th sample is used for testing (Leave one out principle). The error between the predicted value and the measured value of the test sample is compared for a varying SOM grid size between 6 × 6 and 10 × 10. This procedure is repeated to ensure that each sample is used as a test sample only once.

2.6. Redesigning the trochlear groove

The hypothesis can now be tested. The normal trochlear shape is predicted for each of the four femurs that present with trochlear dysplasia. The plane containing the arc centres is positioned first by rotating it around the flexion-extension and internal-external axis and then translating it proximally by the amount prescribed by the artificial neural network. The AP dimension as well as the arc radii are predicted for each of the nine arcs. For each arc, the positioning of a line parallel to the posterior condylar plane indicating the appropriate AP dimension is positioned. Then the centre point on the plane containing the centres is determined. Finally, the arc representing the normal circular geometry of the trochlear groove is created (Fig. 8). Nine surface curves are created and the original dysplastic surface is then morphed to be coincident with the nine surface curves (3Matic 6.0, Materialise, Leuven, Belgium) (Fig. 9).

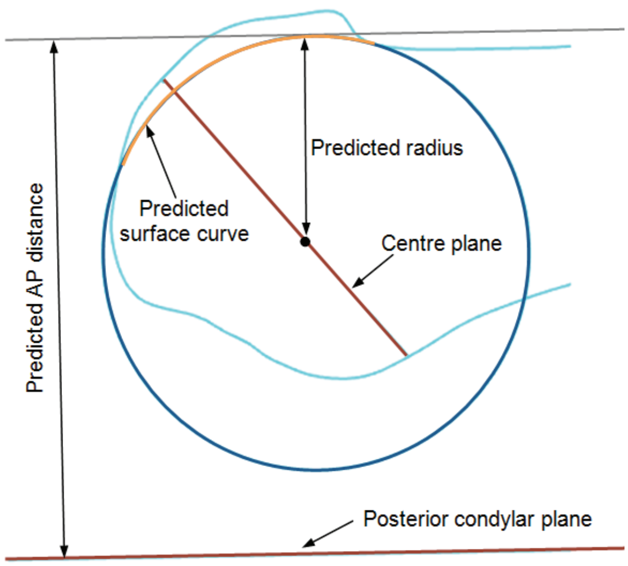

Fig. 8. Predicting the normal curve on a medial sagittal slice (M2)

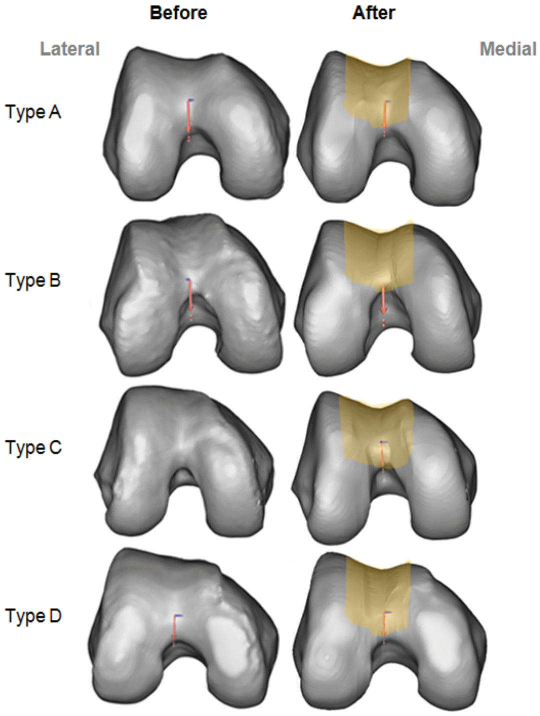

Fig. 9. Change in the AP dimension after redesigning the dysplastic trochlear groove

3. Results

3.1. Measurement framework, curve generation and analysis

The study relies on a reproducible (inter-observer variability) and repeatable (methodological variability) measurement framework. This is shown to be 5.30% of the total variability. This means that the difference in the measurement value is mainly due to the shape of the femur, and only 5.30% of it is due to the error introduced during the measurement. The measurement framework is viable, since the trochlear groove is shown to be circular in the sagittal plane of the measurement framework. Circular arcs coincide with the sagittal trochlear outlines from 40° to 90° of the trochlear flexion angle, depending on what slice is considered. The deviation between the trochlear groove and the circular arc ranges between 0.03 and 0.5 mm, with a mean of 0.2 mm. For each of the 15 femurs considered, the nine arc centres points are co-planar within a 1 mm tolerance. The average orthogonal distance between the centre plane and the centre points is 0.5 mm.

3.2. Artificial neural network

Since no relation of the position of the centre plane between the femurs can be established, the SOM is implemented to relate the AP dimension, the nine radii of the trochlea and the location of the centre plane to one another. The average error between the position of the centre plane predicted with SOM (10 × 6 grid size), and the original values of the normal femurs are 5 and 6 degrees for rotation along the flexion-extension and internal-external rotation axes, and 1.1 mm for translation among the proximal-distal axis. The average error between the measured radii and the predicted radii for the arcs is 2.8 mm (9 × 8 grid size), whereas the average error in the AP dimensions is 1.3 mm (8 × 6 grid size). The average error between the predicted and the measured trochlear heights is 1.5 mm (10 × 9 grid size). At the given grid sizes of the SOM, it yields the maximum agreement between the measurement and the prediction with an average agreement of 91.9%, compared to the worst case of 89.8% agreement with a different set of grid sizes.

3.3. Redesigning the trochlear groove

The SOM prediction suggests a reduction in the central trochlear heights for all four cases considered, while the change in the lateral height is less than 1 mm (Table 2). The medial and lateral trochlear heights remained the same, whereas the central trochlear height has to be decreased by 2.2 mm for the femur with Type A dysplasia. For the femur with Type B dysplasia, the medial and central trochlear heights have to be reduced by 5.1 mm and 4.3 mm, respectively, whereas the lateral trochlear height remains unchanged. The central trochlear height of the femur presenting with type C dysplasia is reduced by 5.2 mm, and the lateral and medial trochlear heights remain unchanged. Lastly, the central trochlear height is reduced by 3.7 mm, whereas the medial and the lateral heights are unchanged in the femur presenting with Type D dysplasia. Redesigning the trochlear grooves has the following effect (Tables 2 and 3):

- The trochlear depth is increased.
- The ventral trochlear prominence is corrected.
- The sulcus angle is corrected.
- The lateral tilt inclination increases.
- The lateral trochlear height remains unchanged.

Table 2. Suggested changes on AP dimensions according to the artificial neural network prediction

Dysplasia	Lateral AP dimension	Central AP dimension	Medial AP dimension
Type A	No change	Decrease	No change
Type B	No change	Decrease	Decrease
Type C	No change	Decrease	No change
Type D	No change	Decrease	No change

Table 3. Femoral parameters before and after redesigning the dysplastic femurs

Parameter	Type A		Type B		Type C		Type D	
	Abnormal	**Redesigned**	Abnormal	**Redesigned**	Abnormal	**Redesigned**	Abnormal	**Redesigned**
Trochlear depth [mm]	2.5	**4.7**	4.1	**5.6**	2.7	**6.3**	2.2	**5.5**
VTP [mm]	1.8	**0.0**	3.2	**0.0**	5.4	**0.0**	5.9	**0.0**
Sulcus angle [degrees]	155	**140**	148	**139**	151	**133**	163	**141**
Trochlear facet symmetry [%]	39.0	**59.1**	69.9	**65.9**	35.1	**58.1**	76.2	**57.1**
LTI [degrees]	14	**20**	11	**21**	15	**27**	12	**20**

4. Discussion

The purpose of this study is to test a hypothesis that the trochlear groove geometry can be predicted if the axis containing the centre points of arcs describing the trochlear geometry can be reliably determined. Although we are able to show that the trochlear groove can be considered circular in sagittal slices spanning the width of the groove, the centre points do not coincide in one axis. This shows that the medial and the lateral facets of the trochlea cannot be described with two spheres on each side. Iranpour et al. (2010) [15] did however show that the centre point of an arc coincident on the trochlear centre is coincident with the femoral flexion axis. However, their study did not consider the entire mediolateral shape of the groove.

The centre points of the arcs are coplanar, and the objective is to test if this plane, defined as the centre plane, can be accurately positioned. Since no linear relationship between the centre planes of the femurs considered can be established, an artificial neural network is constructed to predict the position of the plane.

The AP dimensions (average agreement: 97.8%) are the more reliable guideline for positioning the centre point of these circular arcs than the location of the centre plane (average agreement: 78.8%) defined by the rotations around the ab-adduction and extension-flexion axes and the translation along the internal-external rotation axis from the distal plane. The location of the centre plane determines the distal-proximal location of the centre point of the arcs, influencing the shape of the trochlear groove in the distal-proximal direction to a greater extent, whereas the AP dimensions determine the anterior-posterior location of the circular arc, which influenced the proximal femoral geometry. These imply that the proximal region of the trochlea is more accurately described in this study than the distal region.

Three trochleoplasty procedures have been described in literature: a lateral facet elevation, a sulcus deepening trochleoplasty, and a sulcus depression trochleoplasty. A lateral facet elevation is less invasive and surgically less demanding in comparison to the deepening and compression procedure [16], but it may result in an excessive trochlear prominence that will increase the patellofemoral reaction force. A sulcus deepening trochleoplasty results in proximal realignment without the elevation, but patellofemoral congruency may however be affected negatively. It is also more invasive in comparison to a lateral facet elevation [16]. A depression trochleoplasty, with a retro trochlear wedge resection, is suitable when there is an excessive anterior trochlear prominence (supra trochlear spur) [17]. This procedure is technically less demanding and invasive than a sulcus deepening trochleoplasty. It decreases the prominence of the proximal trochlea while the sulcus angle and the patellofemoral congruency are maintained.

None of the four cases we considered suggested a lateral facet elevation, but the cases considered indicate that either a sulcus deepening or a sulcus depression trochleoplasty will be an appropriate treatment regime. This result is consistent with the previous observations [18] that show that the average of medial and central trochlear heights of the dysplastic group are statistically significantly higher than the values of the normal group while the lateral trochlear heights show no statistically significant difference between the two groups. This is supported with our case study with the following outcomes of the SOM prediction: the average suggests that the central and medial trochlear height reduction is 4.0 mm and 1.3 mm, respectively, compared to the average suggested change in lateral height of less than 0.5 mm.

Lateral facet elevation trochleoplasty is also an unsuitable choice for all types of dysplasia considered. For the Type A femur, trochleoplasty is considered inappropriate since its ventral trochlea prominence (VTP) is within normal range. For these cases medial patellofemoral ligament (MPFL) reconstruction with or without tibial tubercle osteotomy may be a more suitable and effective treatment strategy, depending on patellar alignment and the laxity of the MPFL and the tibial tuberosity–trochlear groove (TTTG) distance, which is outside the scope of this study.

The Type B femur has trochlear facet asymmetry within the normal range but the lateral tilt inclination (LTI) value indicates dysplasia. It has the deepest groove amongst the four dysplastic knees, having the trochlear depth higher than 4 mm and the sulcus angle less than 150°. This suggests that a trochlea depression procedure is an appropriate choice since it has a sufficiently deep groove but with a high VTP. The low LTI can also be corrected by resection of a thicker wedge on the medial than the lateral side. The resurfaced models show that sulcus deepening will be the appropriate choice for both the Type C and D femurs, since the trochlear depth and sulcus angle is abnormal with a high VTP. The trochlea depression trochleoplasty will be unable to correct the surface geometry of the trochlea.

The redesigning of the trochlea and the indication of a trochleoplasty was selected according to the prominence and the deepness of the trochlea. One major advantage of this technique is that the proximal-distal length and the height of the trochlea of a knee can be addressed and compared to the normal trochlear geometry for the given mediolateral dimension. This allows a surgeon to identify the cause of the abnormality of a dysplastic trochlea.

In summary, the corrected geometry produced parameters that are comparable to normal femoral values described in literature, increased trochlear depth and decreased sulcus angle. The change in the LTI (93% increase) was relatively higher than the changes in the trochlear depth, sulcus angle and trochlear facet asymmetry ratio (36%, 6% and 6% increases, respectively) in the Type B femur. This demonstrates that this method is able to correct the morphology that is responsible for dysplasia along with the trochlear depth and sulcus to within a normal range.

Depression trochleoplasty will be the most appropriate procedure for the knees with a congruent patella and femur set and with a relatively deep trochlear groove since it does not alter the shape of the trochlea. On the other hand, the sulcus deepening can correct the alignment and congruency of the patella and femur.

One of the limitations is that the effect of a trochleoplasty on the congruency between the trochlea and its patella was not studied. Patella stabilisation can be achieved by trochleoplasty but we are unsure of what effect this will have on the possible progressive degeneration in the patella femoral joint due to the possible disturbance of the joint congruency. Neither have we considered changes to the effective patellofemoral moment arm. Another limitation of this work is that we only offer evidence of the benefit of the technique on four virtual subject-specific knee models. We are in the process of designing an *in-vitro* study, similar to the study described by Quintelier et al. [19], where we will test the validity of this technique empirically.

5. Conclusion

This work proposes a method for visualising the appropriate type of trochleoplasty that can be considered a plausible solution to dysplasia by making use of an artificial neural network and the knee parameters that are unaffected by the trochlear dysplasia. The clinical significance of this work is that the surgeons can visualise the predicted normal geometry with a three dimensional model prior to the surgery. This provides a means to identify whether and which type of trochleoplasty might serve to solve trochlear dysplasia.

This study demonstrates that an artificial neural network can be used to predict the normal geometry quantitatively for a knee with trochlear dysplasia using various femoral parameters to train the network. The advantage of this method is that more parameters can be incorporated and their relationship can be predicted in a relatively simple way. Patellofemoral parameters such as patella tilt and height can be added to the database to examine the location of the patella as the continuation of this study.

Acknowledgements

We would like to thank Dr. Van Wagening and Partners, Stellenbosch MediClinic, for the CT scans. A word of thanks goes to the volunteers who took part in this study. Funding for this study was obtained from the Department of Mechanical and Mechatronic Engineering, Stellenbosch University.

References

[1] AHMED A.M., DUNCAN N.A., *Correlation of patella tracking pattern with trochlear and retropatellar surface topographies*, J. Biomech. Eng., 2000, 122,652–660.

[2] BALCAREK P., JUNG K., AMMON J., WALDE T.A., FROSCH S., SCHUTTRUMPF J.P., STURMER K.M., FROSCH K., *Anatomy of lateral patellar instability*, Am. Journal Sports Med., 2010, 38, 2320–2327.

[3] FARAHMAND F., SENAVONGSE W., AMIS A.A., *Quantitative study of the quadriceps muscles and trochlear groove geometry related to instability of the patellofemoral joint*, J. Orthop. Res., 1998, 16, 136–143.

[4] JAFARI A., FARAHMAND F., MEGHDARI A., *The effects of trochlear groove geometry on patellofemoral joint stability – a computer model study*, Proc. Inst. Mech. Eng. H, 2008, 222, 75–88.

[5] CARRILLON Y., ABIDI H., DEJOUR D., FANTINO O., MOYEN B., TRAN-MINH V.A., *Patellar instability: Assessment on MR imagesby measuring the lateral trochlear inclination-initial experience*, Radiology, 2000, 216, 582–585.

[6] DEJOUR H., WALCH G., NOVE-JOSSERAND L., *Factors of patellar instability: An anatomic radiographic study*, Knee Surg. Sports Traumatol. Arthrosc., 1994, 2, 19–26.

[7] ESCALA J.S., MELLADO J.M., OLONA J.M., GINE M., SAURI A., NEYRET P., *Objective patellar instability: MR-based quantitative assessment of potentially associated anatomical features*, Knee Surg. Sports Traumatol. Arthrosc., 2006, 14, 264–272.

[8] VARADARAJAN K.M., FREIBERG A.A., GILL T.J., RUBASH H.E., LI G., *Relationship between three-dimensional geometry of the trochlear groove and in vivo patellar tracking during weight-bearing knee flexion*, J. Biomech. Eng., 2010, 132, DOI: 10.1115/1.4001360.

[9] BARINK M., VAN DE GROES S., VERDONSCHOT N., DE WAAL MALEFIJT M., *The trochlea is bilinear and oriented medially*, Clin. Orthop. Relat. Res., 2003, 411, 288–295.

[10] IRANPOUR F., MERICAN A., DANDACHLI W., AMIS A.A., COBB J.P., *The geometry of the trochlear groove*, Clin. Orthop. Relat. Res., 2010, 468, 782–788.

[11] BIEDERT R., SIGG A., GAL I., GERBER H., *3D representation of the surface topography of normal and dysplastic trochlea using MRI*, Knee, 2011, 18, 340–346.

[12] KOHONEN T., SOMERVUO P., *How to make large self-organizing maps for nonvectorial data*, Neural Netw., 2002, 15, 945–952.

[13] DEJOUR D., REYNAUD P., LECOULTRE B., *Douleur et instabilité rotulienne, essai de classification*, Medecine et Hygiene, 1998, 56, 1466–1471.

[14] KOSEL J., GIOUROUDI I., SCHEFFER C., DILLON E., ERASMUS P., *Anatomical study of the radius and centre of curvature of the distal femoral condyle*, J. Biomech. Eng., 2010, 132, DOI: 10.1115/1.4002061.

[15] IRANPOUR F., MERICAN A.M., BAENA F.R.Y., COBB J.P., AMIS A.A., *Patellofemoral joint kinematics: The circular path of the patella*, J. Orthop. Res., 2010, 28, 589–594.

[16] DEJOUR D., LECOULTRE B., *Osteotomies in patello-femoral instabilities*, Sports Med. Arthrosc., 2007, 15, 39–46.

[17] GOUTALLIER D., RAOU D., VAN DRIESSCHE S., *Retro-trochlear wedge reduction trochleoplasty for the treatment of painful patella syndrome with protruding trochleae. Technical note and early results*, Rev. Chir. Orthop. Reparatrice. Appar. Mot., 2002, 88, 678–685.

[18] BIEDERT R.M., BACHMANN M., *Anterior-posterior trochlera measurements of normal and dysplastic trochlea by magnetic resonance imaging*, Knee Surg. Sports Traumatol. Arthrosc., 2009, 17, 1225–1230.

[19] QUINTELIER J., LOBBESTAEL F., VERDONK P., DE BAETS P., ALMQVIST F., *Patellofemoral contact pressures*, Acta of Bioeng. Biomech., 2008, 10, 23–28.