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Original Articles

The quantitative influence of current treatment options on patellofemoral stability in patients with trochlear dysplasia and symptomatic patellofemoral instability - a finite element simulation

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ABSTRACT

Background: Trochlear dysplasia is highly associated with patellofemoral instability. The goal of conservative and surgical treatment is to stabilize the patella while minimizing adverse effects. However, there is no literature investigating the quantitative influence of different treatment options on patellofemoral stability in knees with trochlear dysplasia. We created and exploited a range of finite element models to address this gap in knowledge.
Methods: MRI data of 5 knees with trochlear dysplasia and symptomatic patellofemoral instability were adapted into this previously established model. Vastus medialis obliquus strengthening as well as double-bundle medial patellofemoral ligament reconstruction and the combination of medial patellofemoral ligament reconstruction and trochleoplasty were simulated. The force necessary to dislocate the patella by 10 mm and fully dislocate the patella was calculated in different flexion angles.
Findings: Our model predicts a significant increase of patellofemoral stability at the investigated flexion angles (0°-45°) for a dislocation of 10 mm and a full dislocation after medial patellofemoral ligament reconstruction and the combination of medial patellofemoral ligament reconstruction and trochleoplasty compared to trochleodysplastic ($P = 0.01$) and healthy knees ($P = 0.01–0.02$). Vastus medialis obliquus strengthening has a negligible effect on patellofemoral stability.
Interpretations: This is the first objective quantitative biomechanical evidence supporting the place of medial patellofemoral ligament reconstruction and medial patellofemoral ligament reconstruction combined with trochleoplasty in patients with symptomatic patellofemoral instability and trochlear dysplasia type B. Vastus medialis obliquus strengthening has a negligible effect on patellar stability at a low total quadriceps load of 175 N.

1. Introduction

A multitude of anatomical factors influence patellofemoral stability (Atkin et al., 2000; Bollier and Fulkerson, 2011; Dejour et al., 1994; Dejour and Locatelli, 2001; Nomura et al., 2000; Panni et al., 2011; Wiberg, 1941). While the static (Dejour et al., 1994; Malghem and Maldague, 1989; Senavongse and Amis, 2005) and passive (Fithian et al., 2001; Hautamaa et al., 1998; Teitge et al., 1996) stabilizers have a greater influence from 0 to 40° of flexion, the active stabilizer (quadriceps muscle) have an increasing influence in greater flexion (Fithian et al., 1995).

The initial management after first-time patellar dislocation remains unclear (Sillanpää and Mäenpää, 2012; Smith et al., 2015). The goal of conservative treatment is to restore knee function and range of motion. Traditionally specific strengthening exercises for the vastus medialis obliquus (VMO) are applied while the optimal physiotherapy regime remains controversial (Camanho et al., 2012; Garth et al., 1996; Smith et al., 2010).

When conservative treatment fails, surgical therapy is performed depending on the assessed pathologies. The goal of surgical intervention

Abbreviations: FE, finite element; MPFL, medial patellofemoral ligament; VMO, Vastus medialis obliquus.

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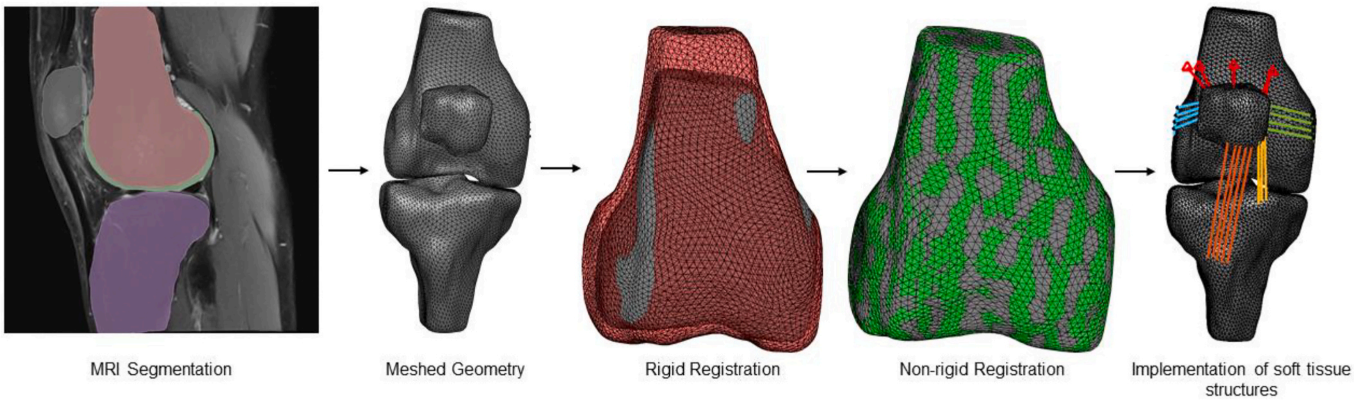

Fig. 1. Workflow for the model creation of a new knee. Rigid and non-rigid registration is performed separately on femur, tibia and patella. In the rigid and non-rigid registration (here at the example of the femur), the red femur represents the template, the grey femur is the new femur and the green femur illustrates the adapted geometry of the new femur. The quadriceps muscle (red), MPFL (green), MPML (yellow), lateral retinaculum (blue) and patellar tendon (orange) are visualized. (Kaiser et al., 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is (a) reconstruction of the MPFL (b) reduction of the severity of the trochlear dysplasia (trochleoplasty) as well as (c) realignment of the extensor mechanism (medializiation of the tibial tuberosity, correction of the leg axis, lateral lengthening). The clinical results of surgical treatment of patellar instability are good (Arendt, 2009; Bereiter and Gautier, 1994; Chassaing and Tremoulet, 2005; Schöttle et al., 2009) in short- and long-term (Nomura et al., 2007; Von Knoch et al., 2006), while early osteoarthritis remains a major concern in these patients (Dejour and Allain, 2004; Grelsamer et al., 2008; Rouanet et al., 2015). Cartilage breakdown is potentially adversely affected by surgical treatment as MPFL malpositioning (Elias and Cosgarea, 2006; Watson et al., 2015), trochleoplasty and medialization of the tibial tuberosity (Elias et al., 2004; Kuroda et al., 2001) may increase patellofemoral cartilage pressure. Knowledge of the quantitative effect of surgical interventions may help achieve sufficient patellofemoral stability while minimizing the number of necessary procedures and thus possibly reducing adverse effects.

To our best knowledge, we are unaware of any investigation on the quantitative influence of VMO strengthening and frequently performed interventions on patellofemoral stability in patients with symptomatic patellofemoral instability and trochlear dysplasia. As this patient collective has a uniquely different anatomy (Panni et al., 2011; Wiberg, 1941), we believe that by investigating these patients we will more closely represent reality than by investigating healthy knees (Amis et al., 2008; Conlan et al., 1993; Desio et al., 1998; Farahmand et al., 1998; Farahmand et al., 2004; Marumoto et al., 1995; Nomura et al., 2000; Senavongse et al., 2003).

The goal of this current study is to exploit a range of previously validated FE models (Kaiser et al., 2021) to investigate the quantitative effect of VMO strengthening, MPFL reconstruction and the combination of MPFL reconstruction and trochleoplasty on lateral patellofemoral stability in different flexion angles.

Our hypotheses are that (a) VMO strengthening will increase patellofemoral stability throughout the investigated flexion angles (0–45°) (b) MPFL reconstruction and (c) combined MPFL reconstruction and trochleoplasty will substantially increase patellofemoral stability in early flexion angles (0–30°).

2. Methods

2.1. Ethical approval

Approval of the ethics committee (BASEC Nr. 2018–01447) and informed consent of all patients was obtained.

Table 1
Demographic data and anatomical properties of the knees with trochlear dysplasia.

Side	Left	Right	Left	Left	Right
Sex	F	M	M	F	F
Age [a]	23	20	25	15	20
Height [cm]	175	173	191	173	176
Weight [kg]	63	63	109	82	60
Trochlear dysplasia (Déjour)	B	B	B	B	B
Patellar dysplasia (Wiberg)	III	III	III	III	III
Leg axis [°]	1 valgus	2 valgus	1 varus	2 valgus	2 valgus
Lat. Trochlear inclination [°]	7	5	7	4	10
Femoral Torsion [°]	26	8	7	7	n/a
TT-TG [mm]	19	18	21	12	7
Patellar height (Caton Deschamps Index)	1.25	1.06	1.19	1.33	1.24

2.2. Model validation and application

The FE model used for this study has been successfully validated in a previous study (Kaiser et al., 2021). MR image data of five healthy adult knee joints were selected to have a comparable cohort to the six fresh frozen cadaver knees used in the literature (Amis et al., 2008; Farahmand et al., 2004). The patients had no history of patellar instability and no anatomical risk factors. None of the patients had a trochlear or patellar dysplasia, TT-TG was <10 mm, patellar height was normal (Caton-Deschamps Index 0.75–0.89) and lateral trochlear inclination was >16°. The MRI DICOM data was segmented semi-automatically and improvement of the models mesh was performed according to Kumara and Pietroni (Kumara, 2011; Pietroni et al., 2009). Contact behavior between the femur and the patella was modelled as frictional with a friction coefficient of 0.02 (Oungoulian et al., 2015; Shah et al., 2015). Cartilage was modelled using rigid surface elements and deformation was taken into account by formulating elastic contact behavior with a contact stiffness 0.5 N/mm^3 and an additional penetration penalty. In an effort to provide best possible comparability for the validation (Viceconti et al., 2005) of the model to the literature (Amis et al., 2008) the same anatomical structures were included *i.e.* quadriceps muscle, capsule and retinacular structures (Fig. 1). In a second step the MR image data of five patients with symptomatic patellar instability who had undergone surgical stabilization at our institution were segmented from the MRI performed prior to the surgery in the same manner to obtain the FE models for simulation of muscle strengthening as well as

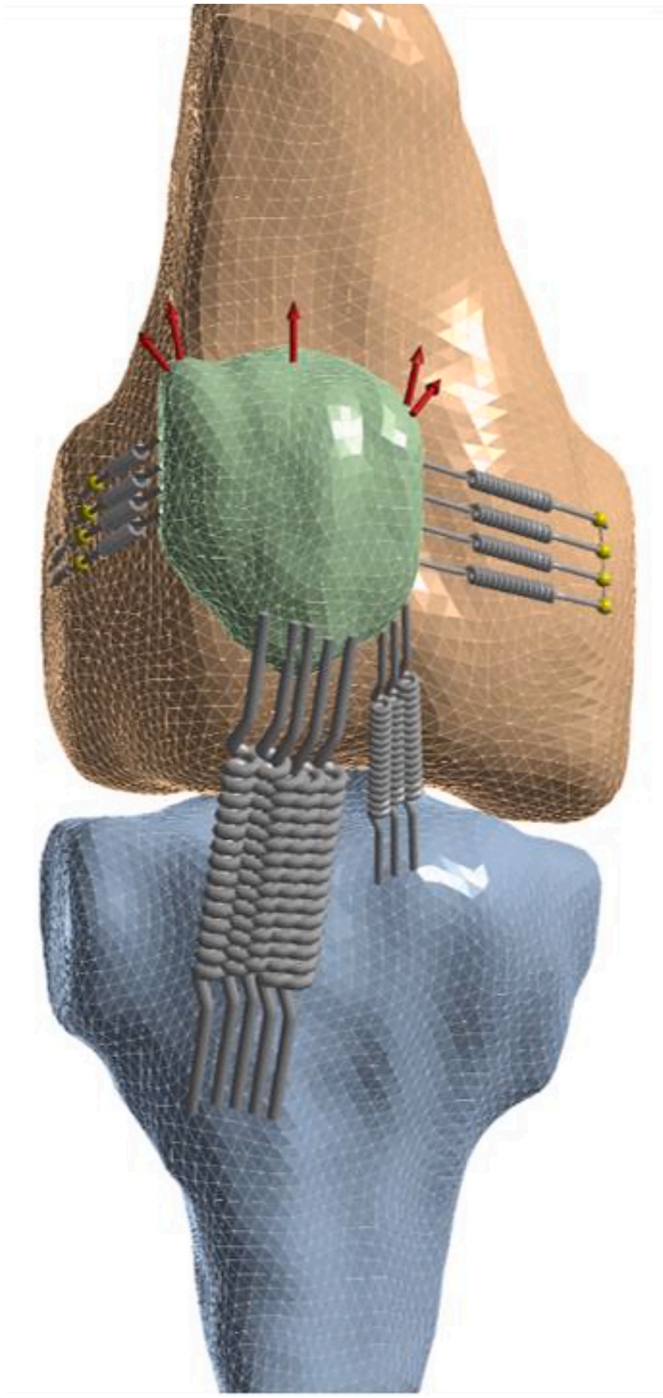

Fig. 2. The image depicts the FE model of a right knee including the simulated anatomic structures (medial patellofemoral ligament, lateral retinaculum, patellar ligament, medial patellomeniscal ligament). The red arrows depict the vectors of the different heads of the quadriceps muscle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

frequently performed surgical interventions to treat patellar instability Demographic data and anatomical properties of this cohort are summarized in Table 1.

2.3. Muscle strengthening

Strengthening the quadriceps muscle especially the VMO is an important goal of conservative treatment (Smith et al., 2010). Simulation of this desired effect on the quadriceps muscle was achieved by arbitrarily increasing the relative VMO force by 10% from 40 N to 44 N and on the other hand decreasing the force of the remaining quadriceps muscles so as not to change the total quadriceps load of 175 N. The force necessary to lateralize the patella 10 mm and fully dislocate the patella was then calculated. The position of the patella in all flexion angles was noted after lateralization to confirm patellar dislocation.

2.4. Reconstruction of the MPFL

MPFL reconstruction was simulated with a transpatellar gracilis tendon loop in the mid to top third of the patella in accordance with the literature (Aframian et al., 2017) and verified by the senior author (S.F.). Femoral attachment was at the original MPFL origin (Fig. 2). The stiffness of the gracilis double-bundle graft was determined as 84 N/mm (Ciccone et al., 2006). The MPFL was given enough play so that the patella could move a quarter of its width until the MPFL tightened itself as performed intraoperatively at our institution. The force necessary to lateralize the patella 10 mm and fully dislocate the patella was then calculated. The position of the patella in all flexion angles was noted after lateralization to confirm patellar dislocation.

2.5. Combined MPFL reconstruction and trochleoplasty

MPFL reconstruction as described in chapter 3.4 was performed in combination with trochleoplasty as described in a previous study (Kaiser et al., 2021). The force necessary to lateralize the patella 10 mm and the peak force to fully dislocate the patella were calculated. The position of the patella in all flexion angles was noted after lateralization to confirm patellar dislocation.

2.6. Statistical analysis

Statistical analysis was performed using a two-tailed non-parametric independent test (Mann Whitney *U* test) for the comparison of the force values. Differences were considered to be statistically significant for *P*-values <0.05. Results are reported as mean, standard deviation and associated *P*-values if not stated otherwise.

3. Results

The results are summarized in Table 2 and Fig. 3.

VMO strengthening as simulated in this study did not relevantly increase the force necessary to lateralize the patella by 10 mm or fully dislocate the patella over all investigated flexion angles.

Isolated MPFL reconstruction significantly increased the force necessary to lateralize the patella by 10 mm and fully dislocate the patella over all investigated flexion angles compared to the trochleodysplastic knees ($P = 0.01$) and in the flexion angles 0–30° compared to the healthy knees ($P = 0.01$) and to isolated trochleoplasty ($P = 0.01$). The absolute force values were markedly greater near full extension of the knee reaching up to 241 N, in flexion these values continuously dropped to 124 N at 45°.

The combination of MPFL reconstruction and trochleoplasty further increased the force necessary to lateralize the patella by 10 mm and to fully dislocate the patella especially from 20° -45°. At 45° of flexion the force necessary to lateralize the patella was significantly greater than for isolated MPFL reconstruction as well isolated trochleoplasty ($P = 0.04/0.02$) (Kaiser et al., 2021). The force necessary to lateralize the patella by 10 mm and fully dislocate the patella over all investigated flexion angles was significantly greater compared to trochleodysplastic knees ($P = 0.01$), healthy knees ($P = 0.01$) as well as isolated trochleoplasty ($P = 0.01–0.02$).

Table 2
Overview of the force values necessary to dislocate the patella by 10 mm and fully dislocate the patella (peak value) at the different flexion angles. For comparison and statistical analysis the values for knees with trochlear dysplasia and healthy knees from the previous study are depicted as well (Kaiser et al., 2021).

	VMO strengthening			MPFL Reconstruction			MPFL+ trochleoplasty		
Flexion angle	*Dislocation force 10 mm [N]*	*SD*	*Vs. dysp. P=*	*Force 10 mm [N]*	*SD*	*Vs. dysp./ healthy P =*	*Dislocation force 10 mm [N]*	*SD*	*Vs. trochleoplasty/ vs. MPFL/ vs healthy P =*
0°	65	8	n.s.	230	36	0.01/0.01	225	19	0.01/ n.s. /0.01
10°	48	14	n.s.	241	68	0.01/0.01	259	60	0.01/ n.s. /0.01
20°	35	12	n.s.	184	55	0.01/0.01	237	84	0.01/ n.s. /0.01
30°	26	7	n.s.	142	31	0.01/0.01	196	61	0.01/ n.s. /0.01
45°	19	11	n.s.	107	15	0.01/n.s.	260	107	0.01/0.02/0.01

	VMO strengthening			MPFL Reconstruction			MPFL+ trochleoplasty		
Flexion angle	*Peak dislocation force [N]*	*SD*	*Vs. dysp. P=*	*Peak dislocation force [N]*	*SD*	*Vs. dysp./ healthy P =*	*Peak dislocation force [N]*	*SD*	*Vs. trochleoplasty/ vs. MPFL/ vs healthy P =*
0°	65	8	n.s.	230	36	0.01/0.01	225	19	0.01/ n.s./ 0.01
10°	49	13	n.s.	241	68	0.01/0.01	259	60	0.01/ n.s./ 0.01
20°	36	13	n.s.	184	55	0.01/0.01	237	84	0.01/ n.s./ 0.01
30°	28	6	n.s.	155	28	0.01/0.01	196	61	0.02/ n.s./ 0.01
45°	27	10	n.s.	124	10	0.01/0.02	260	107	0.02/0.04/0.01

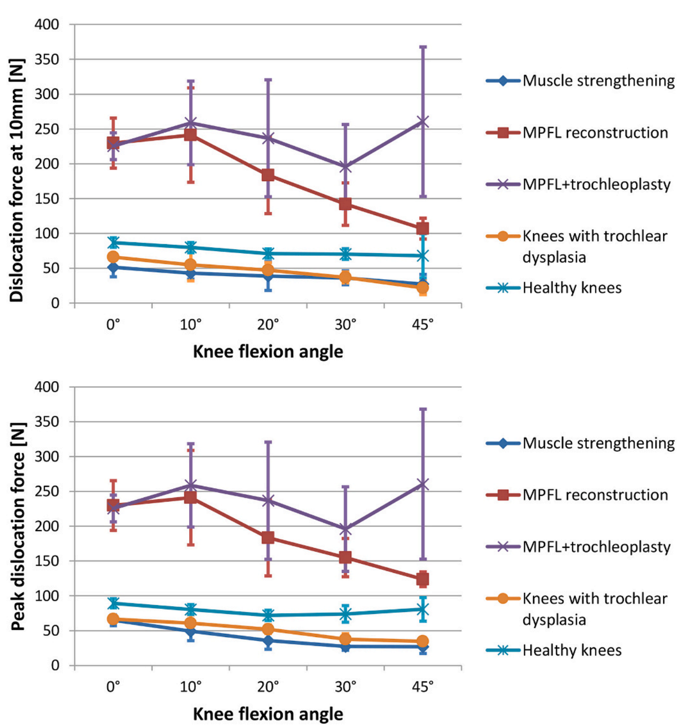

Fig. 3. Diagrams depicting the force necessary to lateralize the patella by 10 mm (top) and to completely dislocate the patella (below) including SD for the different investigated groups. For comparison the values for knees with trochlear dysplasia and healthy knees from a previous study are depicted as well (Kaiser et al., 2021).

4. Discussion

This is the first study to objectively investigate and provide quantitative values of the influence of VMO strengthening and surgical treatment options on lateral patellofemoral stability in knees with symptomatic patellofemoral instability and trochlear dysplasia (Dejour et al., 1998) in different knee flexion angles.

Our model predicts that our arbitrarily chosen simulation of muscle strengthening specifically addressing the VMO had little influence on patellofemoral stability in the investigated flexion angles. This finding surprised us and remains contrary to our hypothesis and must be interpreted with caution for several reasons. An isolated and relative strengthening of the VMO reflects a partial opinion among the different physiotherapeutical approaches in the conservative treatment of patellofemoral instability (Smith et al., 2010). Our model does not take into account the time of activation of the VMO, which is known to have an influence on patellar tracking and patellofemoral pain syndrome (Cowan et al., 2001). Further, we are aware that the applied total quadriceps load of 175 N is rather low compared to everyday loads regularly reaching 1000-2000 N depending on the activity. However, we purposely did not alter the total quadriceps load to improve comparability between the groups. Further studies and simulations with higher quadriceps loads are necessary to evaluate the effect of greater quadriceps load on patellofemoral stability as well as to compare the influence of isolated VMO strengthening to strengthening of the entire quadriceps.

After simulated MPFL reconstruction patellofemoral stability is significantly increased compared to the trochleodysplastic knees at all flexion angles ($P = 0.01$) as well as compared to our healthy knees at 0–30 degree (Table 2, Fig. 1). The stabilizing effect diminishes in greater flexion in accordance with the effect of the native MPFL (Amis et al., 2003) and other FE simulations(Sanchis-Alfonso et al., 2019a; Sanchis-Alfonso et al., 2019b). We believe the pronounced increase of patellofemoral stability is mostly due to the greater stiffness of the gracilis tendon loop of approx. 84 N/mm (Ciccone et al., 2006) compared to the stiffness of the native MPFL which ranges from 8 to 16 N/mm (Amis et al., 2003; Atkinson et al., 2000; Elias and Cosgarea, 2006). Overtightening of this reconstruction must be avoided to minimize adverse effect on the cartilage and on clinical outcome (Elias and Cosgarea, 2006; Ficat et al., 1979; Thaunat and Erasmus, 2009), while tightening the reconstruction to an extent where it sufficiently guides the patella through its range of motion. In everyday clinical practice, we achieve this by giving the MPFL some play, so that it tightens when the patella is shifted about a quarter of its width to the side. As the simulated force values reached up to 241 N it is likely that the femoral attachment of the MPFL reconstruction may fail, before this force is reached in daily life (Mountney et al., 2005).

The combination of MPFL reconstruction with trochleoplasty raises stability increasingly from 20° to 45° of flexion reaching a significant effect at 45° ($P = 0.04$) (Table 2, Fig. 1) compared to isolated MPFL reconstruction. We believe this is due to the increasing engagement of the patella in the trochlear groove, an effect we have also noted in isolated trochleoplasty (Kaiser et al., 2021).

The patellofemoral stability for MPFL reconstruction and combined MPFL reconstruction and trochleoplasty is not only well superior to knees with symptomatic trochlear dysplasia confirming our hypothesis but also to healthy knees possibly reaching levels of patellofemoral stability which may not be necessary.

However, the overall good clinical results only allow us to make cautious suggestions for improvement (Arendt, 2009; Bereiter and Gautier, 1994; Chassaing and Tremoulet, 2005; Nomura et al., 2007; Schöttle et al., 2009; Von Knoch et al., 2006). From a purely biomechanical point of view the stiffness of the gracilis tendon loop is far from anatomical and a single loop or a slimmer tendon may lead to sufficient stability while possibly reducing the risk of adverse effects of overtightening.

The biggest advantage of this work is that we investigated knees with trochlear dysplasia and clinically relevant patellar instability. By segmenting the MRI, we have automatically included clinically relevant anatomical factors such as the patella height, patella position the patellar geometry, the length of the patellar tendon (Neyret et al., 2002) the tibial tuberosity and the trochlear groove. In an effort to minimize cofounders we consciously decided to only include knees with the same trochlear and patellar dysplasia as well as an almost straight leg axis (Table 1). We believe that with this approach we have achieved a simulation as close to reality as possible. The primary advantage of computational modeling is the ability to manipulate the model and vary the input parameters without much effort apart from a long calculation time (Elias and Cosgarea, 2007).

There are numerous limitations to this FE simulation study, but this seemed to be the best way to obtain detailed comparable measurements of patellar stability in knees with trochlear dysplasia as we were unable to obtain such knees *post mortem*. Computational models remain a simplification of reality and the primary concern to computational modeling is the accuracy of the output which is largely dependent on the input parameters. General limitations of the FE model have been discussed extensively (Kaiser et al., 2021). We have limited our investigations to a specific subgroup of knees with symptomatic patellar instability and trochlear dysplasia type B as these are the patients in which trochleoplasty is typically performed at our institution. For other subgroups these results should be treated with caution. Although our FE analysis shows markedly increased patellar stability when combining MPFL reconstruction and trochleoplasty, we cannot state with any assurance that it is needed for successful patella stabilization in view of the efficacy of MPFL reconstruction alone (Liu et al., 2018). Deepening the trochlea relevantly adds stability, as shown in our study, but it may not be necessary. Our investigations were performed at a low total quadriceps load of 175 N as the model validation was performed at this load thus enabling us to compare the results to the literature (Amis et al., 2008) and the healthy knees. At higher quadriceps load the effect of VMO strenghtening is most likely greater, while the relative effect of the investigated surgical procedures may be lower. Further investigation with greater quadriceps load are necessary to confirm this hypothesis. Parameters such as the stiffness of the MPFL have a great influence on the result and may show marked individual variations depending on the diameter, however it will most likely not alter the principal finding. The slack that we implemented corresponds to our intraoperative method, with which we have had very good experience, and has been chosen arbitrarily. Increasing the number of knees ($n = 5$) will most likely not change the principal findings we have made.

5. Conclusion

This is the first objective quantitative biomechanical evidence supporting the place of MPFL reconstruction and MPFL reconstruction combined with trochleoplasty in patients with symptomatic patellofemoral instability and trochlear dysplasia type B. VMO strengthening has a negligible effect on patellar stability at a low total quadriceps load of 175 N.

Declaration of Competing Interest

The authors declare no conflicts of interest that could bias this research, including financial and/or personal relationships with other people or organizations. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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