Studies of the Criteria for Determining Optimal Location of Medial Patellofemoral Ligament Attachment Sites

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18th January 2021

Abstract

Identifying appropriate attachment sites is important in the planning of medial patellofemoral ligament (MPFL) reconstruction. Two criteria are advanced to describe normal MPFL function, namely isometric criterion and desired pattern criterion. Subsequently, computational methods have applied these criteria to determine optimal attachment sites. So far, there is no study that compares the outcomes of these two criteria. For five subjects' 3D models of patella and femur, three patellar sites and many femoral sites were identified as pairs of candidate attachment sites. For each patellar site, the criteria were applied to identify the matching femoral sites that satisfy them, and the matching femoral site with the smallest length change was identified as the optimal femoral site. The desired pattern criterion finds fewer matching sites compared to the isometric criterion. In contrast, the isometric criterion can always find matching sites. The optimal femoral sites obtained vary significantly across different subjects. For most subjects, the optimal sites obtained using the isometric criterion are closer to known anatomical sites than those obtained using the desired pattern criterion. This study reaffirms that MPFL reconstruction is subject specific. The isometric criterion may be more reliable than the desired pattern criterion for determining optimal attachment sites.

1 Introduction

Medial patellofemoral ligament (MPFL) is a thin soft tissue that is attached to the medial side of the patella and the femur. During early flexion, the MPFL is stretched and taut, and it directs the patella to engage the trochlear groove [1, 2, 3, 4, 5]. At about 60° flexion angle, the patella fully engages the trochlear groove. Above 60°, the MPFL is relaxed and the motion of the patella is constrained primarily by the shape of the groove.

MPFL reconstruction is the surgical treatment for restoring the normal function of MPFL [6, 7, 8, 9, 10]. It involves attaching a graft to the medial side of the patella and the femur such that the graft functions like the native MPFL. This is a complex surgical procedure whose outcome is sensitive to many factors including the choice of the graft [7, 9, 11], the graft tension [12, 13], the graft fixation angle [3, 14, 15], and the locations of the attachment sites [13, 16, 17, 18, 19]. Typically, non-artificial graft, such as tendon of quadriceps muscle, is commonly used as the graft of choice, thus availability of the graft is limited. Inappropriate MPFL reconstruction would result in a dysfunctional graft that is too relaxed to pull the patella towards the trochlear groove, or too taut that it over-stretches and causes damage to the knee joint [1, 2, 15, 17, 20, 21].

Two assessment criteria have been advanced to describe the normal function of MPFL. The *isometric* criterion states that the MPFL's length should not change by more than 5% over the full range of knee flexion [3, 21, 22, 23, 24, 25, 26]. In contrast, the *desired pattern* criterion requires the MPFL to remain isometric only between 0° and 60° flexion angle [1, 2, 25, 27, 28]. Above 60°, the MPFL should relax and shrink towards its natural length. Thus, the desired pattern criterion may seem to be more comprehensive than the isometric criterion.

Computational methods have been proposed to identify appropriate attachment sites that support the normal function of the graft [27, 28, 29, 30, 31, 32, 33]. These methods compute the distance between a pair of attachment sites and its change over the full range of knee flexion. Attachment sites that satisfy the assessment criteria are regarded as matching attachment sites. Typically, many matching sites are available, and the pair of sites that offers the least change of distance over the range of knee flexion can be regarded as the optimal attachment sites. Existing methods use only one of the criteria for assessment. No study has compared the strengths and weaknesses of these two criteria.

This study aims to investigate the two assessment criteria and compare their strengths and weaknesses. It also aims to study the significance of the patellar site in determining the optimal femoral site. Therefore, this study could help the surgeons in the planning of MPFL reconstruction.

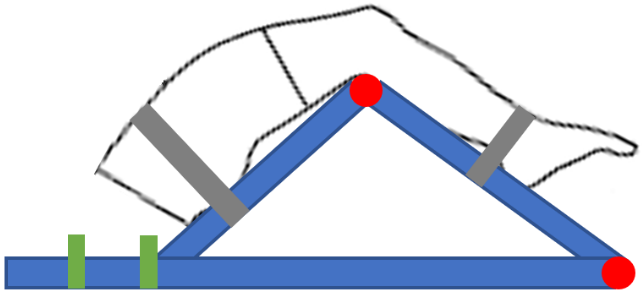


Figure 1: Schematic representation of the experimental setup and the rig. Velcro straps (gray) were used to hold the knee specimen on the wooden boards (blue). The wooden boards were folded at their hinges (red) and fixed by studs (green) to position the knee at certain flexion angle.

2 Methods

2.1 Data Preparation

Five freshly frozen cadavers' knees (S1–S5) with no pathologic findings were used in this study. The knees belonged to four males and one female who were aged between 53 and 78 years old. The soft tissues around knee joint remained intact to maintain normal patellofemoral (PF) joint motion. However, there was no tensioning of the quadriceps, and hence some amount of patellar laxity may exist.

Each cadaver's knee was positioned inside the computed tomography (CT) scanner as follows. The cadaver's knee was strapped onto a jig with the knee in full extension at the start, and the anterior part of the patella is facing upwards (Fig. 1). The straps were placed at distal end of the tibia and at the proximal end of the femur. In particular, they were placed as far as possible from the knee joint so as to minimize any disturbances to the patella kinematics. They prevented any unwanted rotation of the knee. These straps that held onto the leg were tightened each time the knee was flexed or re-positioned.

Once the cadaver's knee was positioned in the CT scanner, CT scans of the knee were captured under standard in-vivo setting at approximately every 30° flexion angle between 0° and 120°. Specifically, the knee was flexed along with the jig to the prescribed flexion angles based on a goniometer measurement. Note that the in-vivo setting was chosen to follow the standard procedure of CT scanning an in-vivo knee in the routine clinical practice. For subjects S1, S2, and S4, their left knees were scanned. For subjects S3 and S5, their right knees were scanned.

The CT scans were used to construct three dimensional (3D) mesh models of PF joint at various flexion angles. First, knee bone regions in the CT scans were manually segmented using a standard thresholding method. Then, 3D knee models were constructed from the segmented CT scans using the marching cubes method [34]. Finally, the 3D knee models at 30°, 60°, 90°, and 120° flexion angle were individually registered to the knee model at 0° flexion angle based on their 3D femoral models using the similarity transformation algorithm [35]. These rigidly registered 3D knee models describe some poses of PF joint motion at a consistent coordinate system. Note that MPFL attachment sites were not

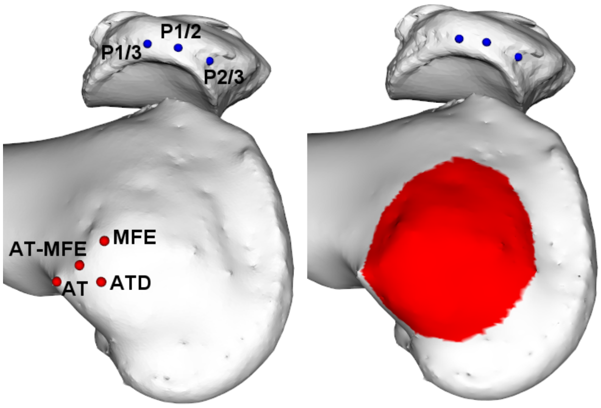


Figure 2: Anatomical and candidate MPFL attachments sites. Blue and red dots denote anatomical patellar and femoral sites, respectively. Red region denotes candidate femoral sites.

segmented from the CT scans because they are not identifiable in the CT scans that are captured under in-vivo setting.

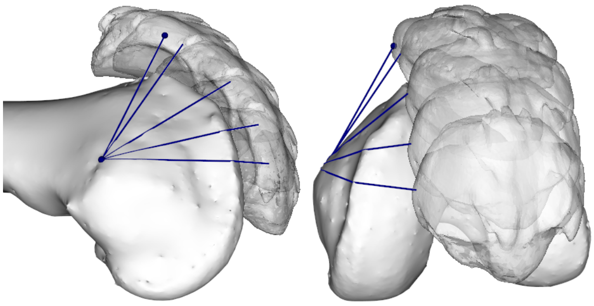
2.2 Candidate Attachment Sites

Existing works [16, 17, 18, 19] considered three anatomical patellar attachment sites, namely proximal one third (P1/3), proximal half (P1/2) and proximal two third (P2/3) (Fig. 2). They reported that the location of the patellar site did not significantly affect MPFL length change pattern, whereas others reported the contrary [3, 22, 27, 29]. For ease of comparison with existing works, this study selects the same three patellar sites to investigate. In a more comprehensive study, more patellar sites will have to be considered.

On the other hand, these existing works considered a large number of candidate femoral sites, and found the femoral site to significantly affect MPFL length change pattern [16, 22, 28, 29]. This study considers the mesh points within the medial epicondyle region as candidate femoral sites (Fig. 2). These mesh points are sufficiently dense to cover all the important surface points that characterize the shape of the medial epicondyle. Moreover, they include the anatomical sites reported in the literature [1, 2, 16, 20], namely the peak of medial femoral epicondyle (MFE), the adductor tubercle (AT), 10 mm distal to AT (ATD) and the saddle point between AT and MFE (AT-MFE). The candidate femoral sites cover much larger area than the anatomical sites to ensure that the optimal femoral site for a specific subject is covered by the candidate sites.

2.3 Determining Optimal Attachment Sites

The MPFL length between a patellar site and a femoral site is estimated by the *geodesic distance* between them (Fig. 3). Specifically, geodesic distance between a pair of attachment sites was computed for all constructed PF joint poses, one at a time, to estimate MPFL length at various flexion angles.



(a) (b)

Figure 3: Visualization of the geodesic distance between a pair of attachment sites at different flexion angles. (a) Medial view. (b) Frontal view.

The geodesic distance is the shortest straight-line distance over the surfaces of the bone models. This approach has been used in previous MPFL modeling studies [28, 29, 30, 31, 32]. The geodesic distance between a pair of sites is expected to increase during early flexion, which corresponds to the tightening of MPFL, and to decrease after early flexion, which corresponds to the relaxation of MPFL. Note that the geodesic distance can be smaller than the MPFL's natural length although a native MPFL only relaxes to its natural length.

Two established criteria that describe the MPFL's length changes are used to assess the feasibility of attachment sites:

1. Isometric Criterion [29, 31, 32, 33]:

   The isometric criterion requires that the MPFL does not stretch too much from MPFL's natural length. In terms of computational modeling, the average difference A of the estimated length (i.e., geodesic distance) l_θ between attachment sites at flexion angle θ relative to the MPFL's natural length (i.e., estimated MPFL's length with no strain) l_n should be smaller than 5%:

$$\begin{aligned} &A = \frac{1}{n}\sum_{i=1}^{n}\frac{|l_\theta - l_n|}{l_n}, \\ &A < 5\%, \end{aligned}$$

   where n is the number of joint poses.

2. Desired Pattern Criterion [1, 2, 25, 27, 28, 36]:

   The desired pattern criterion requires that the MPFL tightens at early flexion and relaxes at late flexion. Computationally, the desired pattern criterion can be formulated as follows:

$$\begin{aligned} 0^\circ \le \theta \le 60^\circ : &\quad l_n \le l_\theta \le l_m, \\ \theta > 60^\circ : &\quad l_\theta < l_n. \end{aligned}$$

   where l_m is the maximum allowed length of the MPFL. The length difference between l_m and l_n is taken to be 5% as suggested by Oka et al.[28]. That is, $(l_m - l_n)/l_n = 5\%$.

Note that l_m is only used in the desired pattern criterion, whereas l_n is used in both criteria. For isometric criterion, the average difference was used instead of other measurement of length variation, such as maximum difference, to mainly maintain consistency with existing studies [29, 31, 32, 33]. Moreover, the maximum difference in isometric criterion implies the positive length changes should be less than 5% because negative length changes can be ignored as it describes MPFL being relaxed. Existing studies [1, 27, 33] also reported that MPFL is most taut around $30° - 60°$. Therefore, such condition is implicitly captured by the desired pattern criterion as the criterion requires the length at flexion angle $\leq 60°$ to be less than 5% from natural MPFL's length.

In this study, natural and maximum MPFL's length of a specific subject is unknown because MPFL cannot be identified from the CT scans. Moreover, there is no consensus at when the MPFL attains its neutral and maximum allowed lengths. Some researchers report that the MPFL is longest and most taut at 0° flexion angle [2, 28, 31, 33, 37] while others report that the MPFL is longest between 30° and 60° flexion angle [1, 27, 33]. As suggested by Oka et al.[28], MPFL should not be stretched by more than 5% from its natural length. Therefore, this study investigates two different modeling options:

- Option 1: The length at 0° (l_0) is the *natural length*, i.e., $l_n = l_0$. In this case, $l_m = 1.05\, l_n = 1.05\, l_0$.
- Option 2: The length at 0° is the *maximum allowed length*, i.e., $l_m = l_0$. In this case, $l_n = l_m/1.05 = l_0/1.05$.

As a result, this study considers the two possible scenarios at which MFPL is most taut.

An exhaustive search algorithm was applied to locate the optimal attachment sites among all pairs of candidate sites. In particular, the algorithm verifies the length changes of each pair of candidate attachment sites with each assessment criterion and modeling option. Note that, for each patellar site, more than one femoral site may satisfy an assessment criterion. These sites are called *matching femoral sites*. Among these matching sites, the one with the smallest average length difference A is selected as the optimal site.

3 Results

3.1 Length Variations of Optimal Sites

As an illustrative example, length variations of subject S3's optimal femoral sites for all patellar sites are chosen (Fig. 4). The length variations of optimal sites satisfy the two optimal criteria with different modelling options. Indeed, the length variations of optimal sites that satisfy the isometric criterion are lower 5% of l_n. Those that satisfy the desired pattern criterion are $\geq l_n$ and $\leq l_m$ between $0° - 60°$, and $< l_n$ between $90° - 120°$; the length variations between $60° - 90°$ are not necessarily $< l_n$ because the PF joint poses at those flexion angles were not acquired in this study, and geodesic distance could

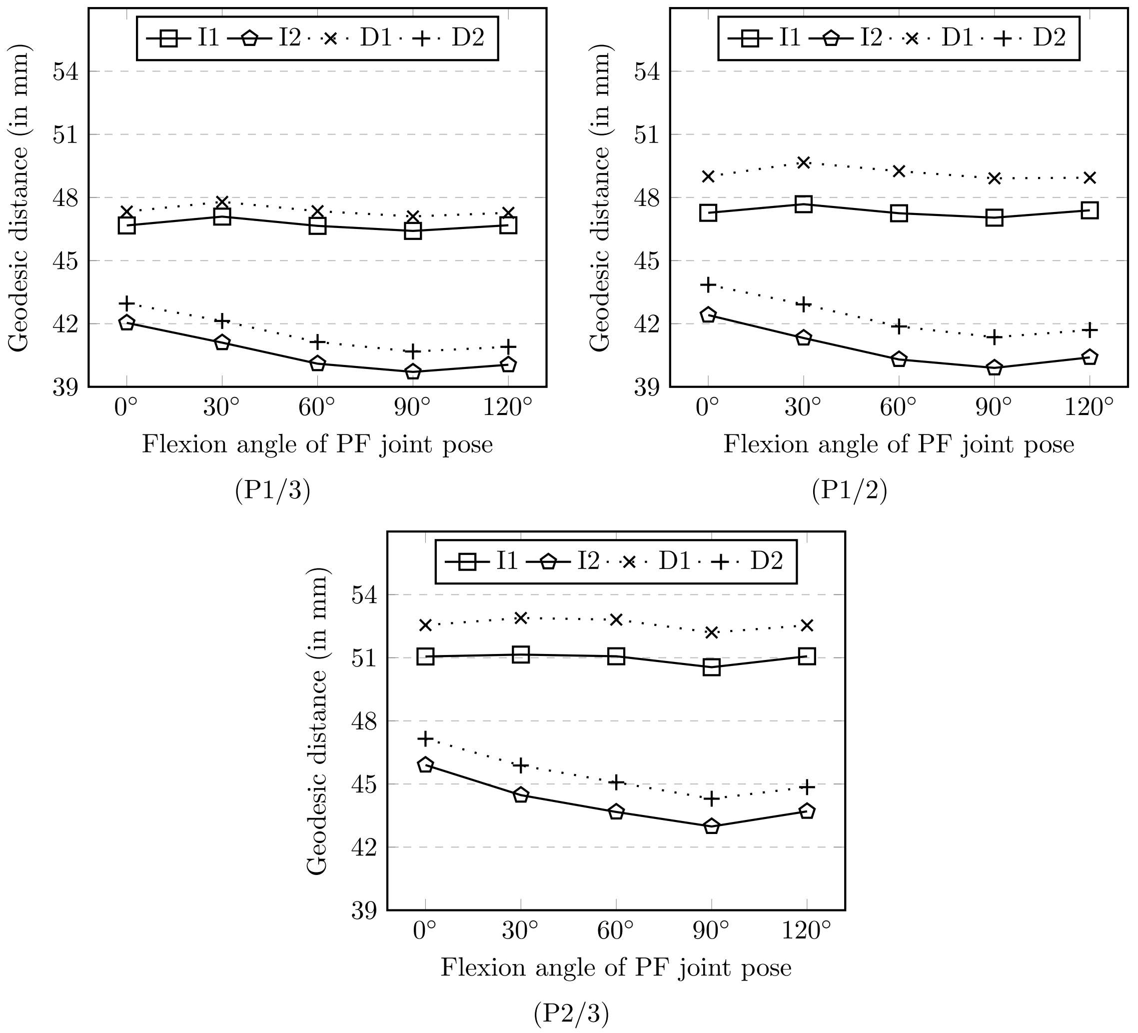


Figure 4: Length variations of optimal femoral site for different patellar sites of subject S3. I1: Isometric, Option 1. I2: Isometric, Option 2. D1: Desired pattern, Option 1. D2: Desired pattern, Option 2.

not be measured. The length variations of the desired pattern criterion are slightly higher than those of isometric criterion. With Option 1, the length variations of optimal sites can be $\geq l_0$ because l_0 is the natural length. With Option 2, the length variations of optimal sites are $\leq l_0$ because l_0 is the maximum allowed length. These length variations of optimal sites are consistent across all subjects and patellar sites.

3.2 Effect of Patellar Site

The location of patellar site affects the lengths of optimal sites (Fig. 4). The geodesic distances between optimal femoral sites and patellar site at P1/3 are slightly smaller than those obtained with patellar site P1/2. On the other hand, those obtained with patellar site P2/3 are significantly larger than those obtained with patellar site P1/3. These results are consistent across subjects.

The location of patellar site also affects the locations and number of matching femoral sites. As expected, the most proximal patellar site (P1/3) has matching femoral sites located more proximally,

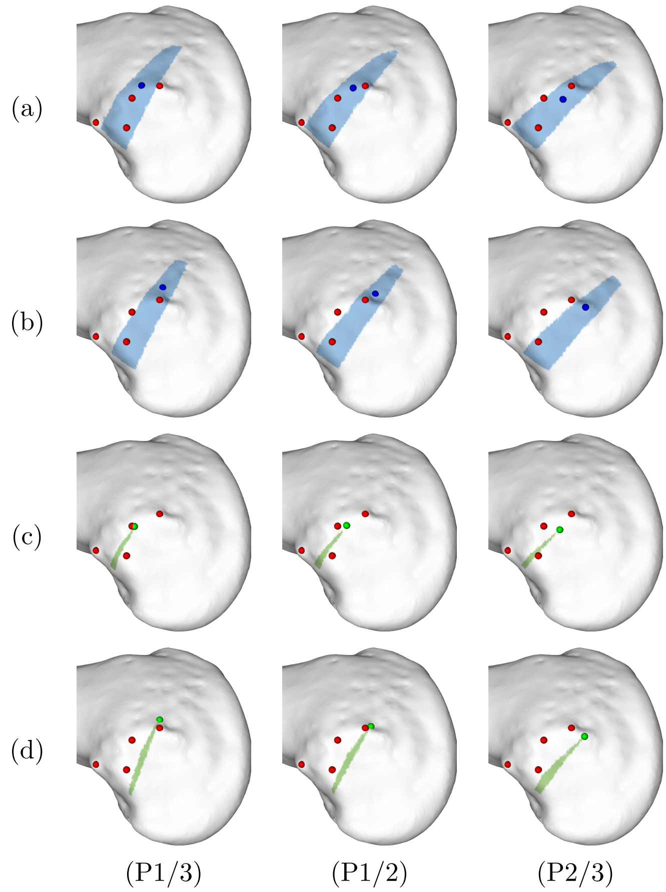


Figure 5: Matching and optimal femoral sites of subject S2. (a) Isometric, Option 1. (b) Isometric, Option 2. (c) Desired pattern, Option 1. (d) Desired pattern, Option 2. Blue and green regions denote matching femoral sites. Blue and green dots denote optimal femoral sites, and red dots denote anatomical sites.

and the most distal patellar site (P2/3) has matching femoral sites located more distally (Fig. 5). This distribution pattern is consistent across different subjects.

The number of matching femoral sites varies for different patellar site. Specifically, with the isometric criterion, the number of matching femoral sites is quite consistent for different patellar site (Fig. 6(a, b)). On the other hand, with the desired pattern criterion, the number of matching femoral sites of some subjects vary quite significantly for different patellar site (Fig. 6(c, d)). In particular, the numbers of matching femoral sites of subject S1 and S3 at P2/3 differ by more than 50% than those at P1/3. Therefore, the location of the patellar site will significantly affect the location of the optimal femoral site.

3.3 Effect of Assessment Criterion

Number of matching femoral sites differ significantly across different assessment criteria. A large number of matching femoral sites are accepted by the isometric criterion, which is about 1500 matching femoral sites (Fig. 5–7(a, b)). They include many known anatomical sites. In comparison, far fewer matching

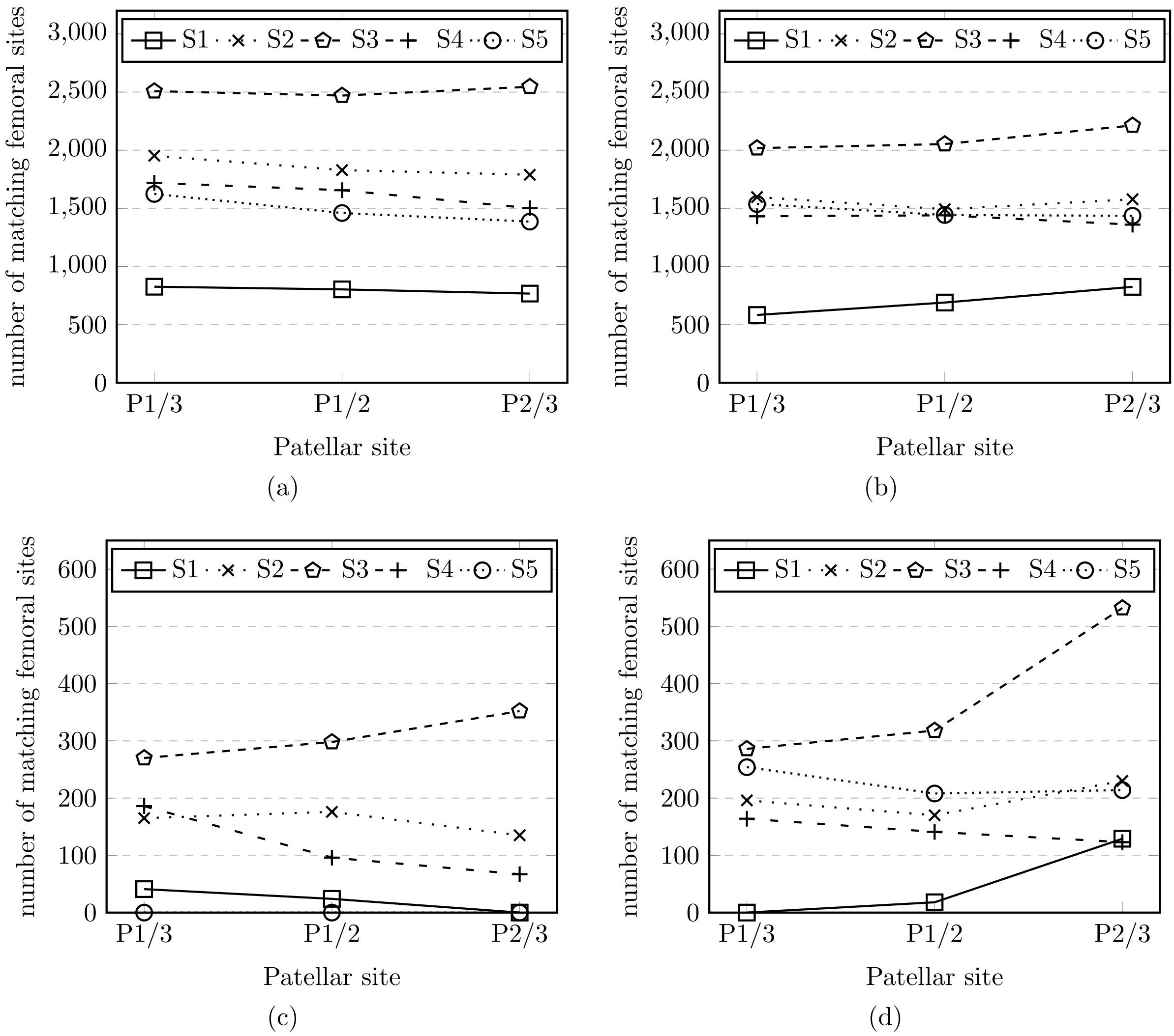


Figure 6: Number of matching femoral sites of each patellar site. (a) Isometric, Option 1. (b) Isometric, Option 2. (c) Desired pattern, Option 1. (d) Desired pattern, Option 2.

femoral sites are accepted by the desired pattern criterion, which is about 300 matching femoral sites (Fig. 5–7(c, d)). They cover smaller and narrower regions compared to those accepted by the isometric criterion.

For both isometric and desired pattern criteria, the matching femoral sites obtained with Option 1 are located more proximally compared to those obtained with Option 2. Moreover, the optimal femoral site obtained with Option 1 are located more posterior within the matching regions compared to those obtained with Option 2 (Fig. 5, 7). This result is due to Option 1 regarding l_0, the length at 0°, as the natural length whereas Option 2 regards l_0 as the maximum allowed length. The distribution of matching femoral sites of the two assessment criteria are consistently more elongated in anterior-posterior direction than in proximal-distal direction.

In the extreme case, the desired pattern criterion cannot find any matching femoral site for subject S1's P2/3 using Option 1 and P1/3 using Option 2 (Fig. 6). It also cannot find matching femoral site for all three patella sites of subject S5 with Option 1 (Fig. 6).

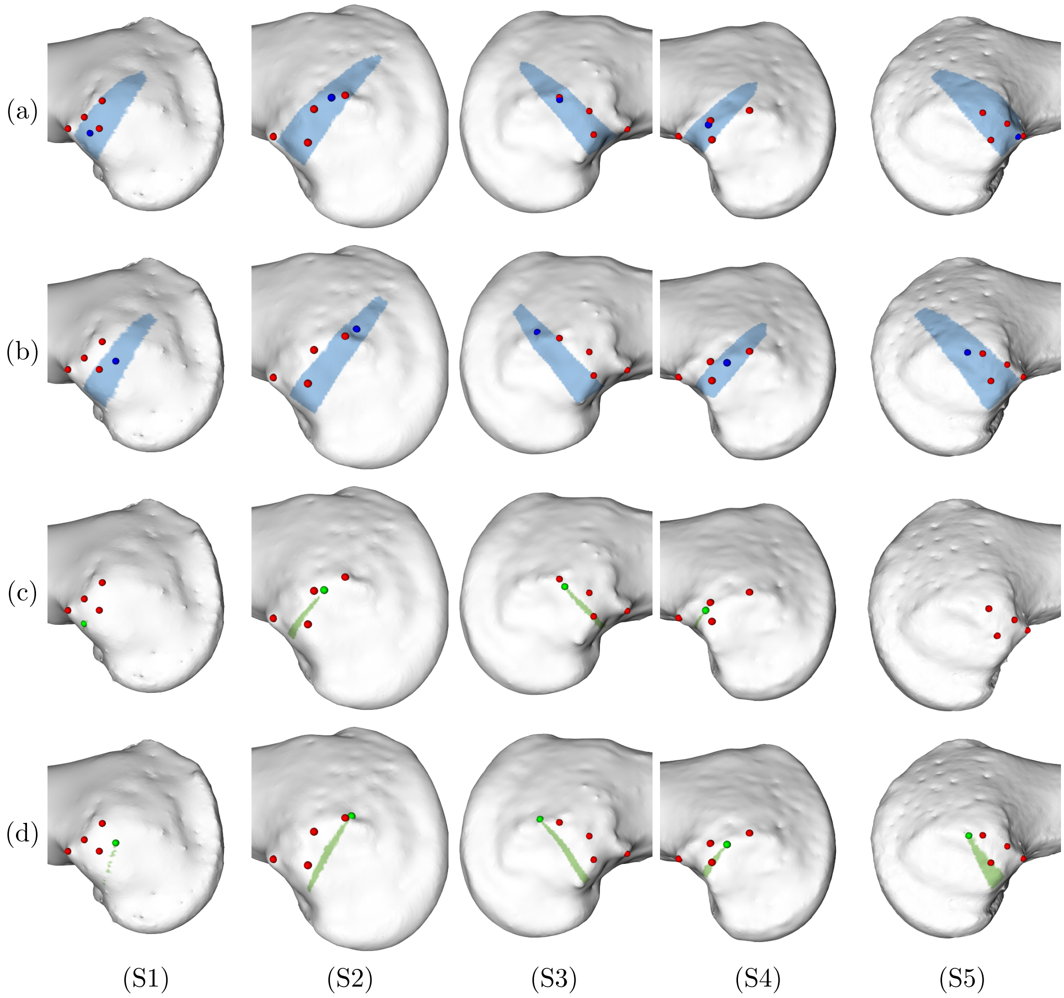


Figure 7: Matching and optimal femoral sites for patella site P1/2. (a) Isometric, Option 1. (b) Isometric, Option 2. (c) Desired pattern, Option 1. (d) Desired pattern, Option 2. Desired pattern criterion with option 1 cannot find matching and optimal femoral sites for subject S5. Blue and green regions denote matching femoral sites. Blue and green dots denote optimal femoral sites, and red dots denote anatomical sites.

To assess the computation results, the distance between an optimal femoral site and its nearest anatomical site was measured (Table 1). For most subjects and most patellar sites, the optimal sites obtained using the isometric criterion with Option 1 are closer to known anatomical sites than those obtained using the other criterion or option. Therefore, isometric criterion with Option 1 may be more reliable than the other criterion or Option in determining optimal femoral site. The desired pattern criterion is favorable only for some subjects and some patellar sites, namely P1/3 with Option 1 and P1/2 with Option 2 (Table 1).

3.4 Subject Variation

The location of the optimal pair of attachment sites differs significantly across subjects (Fig. 7). The optimal femoral site of subject S1 is located near ATD. Those of S2, S3 and S5 are mostly located near MFE, whereas those of S4 are located near AT-MFE. There is no single patellar site that consistently

Table 1: Distance (in mm) between optimal femoral site and its nearest anatomical site. I1: Isometric, Option 1. I2: Isometric, Option 2. D1: Desired pattern, Option 1. D2: Desired pattern, Option 2.

Subject	P1/3				P1/2				P2/3			
	I1	I2	D1	D2	I1	I2	D1	D2	I1	I2	D1	D2
S1	**0.96**	6.44	1.92	-	**3.16**	4.84	5.92	4.84	**3.49**	6.92	-	4.76
S2	4.36	4.57	**0.69**	2.87	3.26	3.97	2.49	**1.85**	**4.27**	4.35	4.46	4.29
S3	0.67	6.62	**0.66**	5.64	**0.74**	6.48	2.60	5.23	**2.62**	8.80	3.01	7.81
S4	2.06	2.92	**1.75**	2.95	**1.02**	4.44	2.16	4.44	**2.62**	4.18	3.53	3.80
S5	**1.78**	4.98	-	4.98	**1.76**	4.07	-	3.71	**2.74**	6.98	-	6.27

gives smallest distance from its optimal femoral sites to their respective nearest anatomical sites across all subjects. In particular, the patellar site P1/3 gives smallest distance from its optimal femoral sites to the nearest anatomical site for subject S1, S2 and S3. On the other hand, those of S4 and S5 are located at P1/2. This subject variation occurs due to the difference in the shapes of the subjects' femurs and patellas.

4 Discussion

This study investigates the effect of using different assessment criteria and modelling options to the location of optimal pair of attachment sites. Similar to some existing works [28, 29], this study includes few patellar sites and many femoral sites, and exhaustively search for the optimal pair of attachment sites among those pairs of candidate sites. This study estimates the MPFL length between a pair of attachment sites as a geodesic distance which is consistent with other computational studies [28, 29, 30, 31, 32], instead of straight-line distance that was typically used in in-vitro studies [1, 38]. The former estimation is more accurate than the latter because the latter does not consider the spanning of the MPFL over the bone surface [31].

This study reveals several findings. First, as expected, the location of optimal pair of attachment sites is subject dependent. The same finding was reported in the previous studies [30, 39]. This finding reaffirms the need to perform subject-specific planning of MPFL reconstruction. Among the three patellar sites, P1/3 and P1/2 typically have optimal femoral sites that are closer to the anatomical sites as compared to those of P2/3. This finding is consistent with existing anatomical studies that consistently reported the location of patellar site to be between P1/3 and P1/2 [16, 17, 18, 19]. On the other hand, the nearest anatomical sites from the optimal femoral sites are different than those found in the existing computational studies [28, 29, 33, 40]. In particular, existing studies reported that optimal femoral site are typically located near ATD or AT-MFE, and not MFE. Even though the results of previous studies are consistent with the results of subject S1 and S4, however, they are in contrast with the results of subject S2, S3 and S5. One possible reason for this inconsistency is due to the small number of subjects used in all studies that are insufficient to capture significantly different anatomical femoral attachment sites across subjects.

Second, the location of patellar site significantly affects the location of optimal femoral site. In particular, more proximal patella site (P1/3) has optimal femoral site located more proximally, whereas more distal patella site (P2/3) has optimal femoral site located more distally. Other than that, the geodesic distances of optimal sites obtained with more proximal patellar site (P1/3) are smaller than those obtained with more distal patellar site (P2/3). These results are consistent with most existing reports that the location of patellar site significantly affects MPFL length change pattern [3, 22, 27, 29, 32], in contrast to [33] that reported no significant effect.

Third, desired pattern criterion accepts fewer matching femoral sites than does isometric criterion. For some subjects, it did not find any matching and optimal femoral site. On the other hand, isometric criterion can always find matching and optimal femoral sites. Moreover, the optimal femoral sites obtained using isometric criterion Option 1 are closest to known anatomical sites compared to those obtained using other criterion or option. On top of that, the optimal pair of attachment sites obtained using isometric criterion have smaller geodesic distances than that of desired pattern criterion, which is preferred in clinical practice as availability of graft is limited. Thus, isometric criterion Option 1 may be more reliable and preferable for clinical practice than the other criterion or option in identifying optimal femoral sites. Also, the distribution of matching sites are more elongated in anterior-posterior direction than proximal-distal direction, which implies the length variations are more similar in the former direction than the latter. The same finding was also reported in existing studies [28, 29, 33, 40] where length variations are more sensitive to changes of femoral sites in the proximal-distal direction than in the anterior-posterior direction.

Lastly, this study also provide insight on the flexion angle for graft fixation. As shown in Table 1, Option 1 always gives the optimal femoral sites that are closest to one of the anatomical sites across different assessment sites and patellar sites, except for subject S2 with patellar site located at P1/2. This result may indicate that the MPFL are most taut between $30^\circ - 60^\circ$ flexion angle, which is consistent with some studies [1, 27, 33]. Since graft fixation is advised to be performed when the MPFL is expected to be most taut, graft fixation should be performed between $30^\circ - 60^\circ$ flexion angle.

This study has several limitations. First, it considers only three candidate patellar sites, which may not have included the optimal patellar site. Technically, increasing the number of candidate patellar sites by including mesh points within the region of medial patella is possible. However, this approach will significantly increase the number of pairs of candidate sites that requires significantly larger computational cost for the exhaustive search algorithm to locate the optimal sites. Second, this study was performed on cadaver knees without bearing loads or tensioning of the quadriceps. The results obtained may differ from those of in vivo knees during load bearing. Third, actual locations of MPFL attachment sites on the cadaver knees were not captured because CT scans were captured under in-vivo setting that is typically used for patient scanning. Thus, accurate evaluation of the results could not be performed. Lastly, more joint poses will be beneficial and possibly needed to ensure detailed length variations are sufficiently captured.

Our follow-up study will address these limitations in the following ways. First, more candidate patellar sites will be included. This will require the development of an efficient algorithm to identify the optimal attachment sites on the patellar and the femur. In this case, the algorithm would be applicable to identify optimal sites of a specific subject in routine clinical practice. Second, computational modeling of knee flexion with load bearing should be adopted such that accurate and detailed joint poses can be obtained. Third, actual locations of MPFL attachment sites on the cadaver knees should be identified to provide ground-truth information for stronger evaluation.

5 Conclusion

This study investigated and compared the isometric criterion and the desired pattern criterion for identifying optimal attachment sites. The results of this study show that the isometric criterion can always find optimal attachment sites, whereas the desired pattern criterion may fail for some subjects. Moreover, the geodesic distances obtained with isometric criterion are smaller than those of the desired pattern criterion. In particular, isometric criterion Option 1, with l_0 regarded as MPFL's natural length, may be more reliable and preferable than the other criterion or option for the planning of MPFL surgery. Moreover, the study results demonstrate the importance of identifying the optimal patellar site, in addition to the optimal femoral site, for the planning of MPFL reconstruction surgery. In particular, the optimal patellar site might be obtained between the proximal one third and proximal half of the patella. On the other hand, the optimal femoral sites are nearest to significantly different anatomical sites, namely MFE, ATD, and AT-MFE. Thus, the optimal pair of attachment sites is subject dependant.

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