In Vivo Length Change of Ligaments of Normal Knees During Dynamic High Flexion

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Abstract

Background

No studies compared the length change of ligaments of normal knees during dynamic activities of daily living. The aim of this study was to investigate in vivo length change of ligaments of the normal knees during high flexion.

Methods

Eight normal knees were investigated. Each volunteer performed squatting, kneeling, and cross-leg motions. Each sequential motion was performed under fluoroscopic surveillance in the sagittal plane. The femoral, tibial, and fibular attachment areas of the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), deep medial collateral ligament (dMCL), superficial medial collateral ligament (sMCL), and lateral collateral ligament (LCL) were determined according to osseous landmarks. After 2D/3D registration, the direct distance from the femoral attachment to the tibial or fibular attachment was measured as the ligament length.

Results

From 20° to 90° withflexion, the ACL was significantly shorter during cross-leg motion than during squatting. For thePCL, dMCL, sMCL, and LCL, there were no significant differences among the 3 motions.

Conclusion

The ACL was shorter during cross-leg motion than during squatting in mid-flexion. This suggests that the ACL is looser during cross-leg motion than during squatting. On the other hand, the length change of the PCL, MCL, and LCL did not change even though the high flexion motions were different.

Background

Soft tissue balance such as ligament balance is one of the most important factors for successful total knee arthroplasty (TKA). In addition, ligament-retained TKA has increased worldwide. Therefore, surgeons now take more interest in the ligament balance of the knee. Many previous studies reported length change to the ligaments of normal knees [1–10]. However, some studies examined the in vitro condition [1, 5, 7]. Regarding in vivo studies, they examined static motions or simple active motions [2–4, 6, 8, 10, 11] such as leg flexion and extension. No studies compared the length change of ligaments of normal knees during dynamic activities of daily living.

Especially in Asia and the middle-east, people commonly bend their knees deeply in daily living, like sitting on the floor and praying. In Western countries, many people perform the squatting position while they play sports. In addition, several studies have demonstrated that the in vivo kinematics of normal knees during high-flexion activities are significantly different [12–14]. Therefore, it is important to investigate the length change during high-flexion motions all over the world. Furthermore, several reports have demonstrated that patients' satisfaction with TKA has been greater with a medial pivot pattern, such as in normal knees [15, 16]. Therefore, we thought that it was necessary to evaluate the length change of ligaments of normal knees during high flexion to further increase patients' satisfaction after ligament-retained TKA.

The aim of this study was to investigate in vivo length change of ligaments of normal knees during dynamic high-flexion activities. The hypothesis of this study was that the length change of ligaments of normal knees was different depending on the high flexion activities of daily living.

Methods

A total of 8 normal knees (4 Japanese healthy male volunteers) were investigated. At the time of the investigation, their mean age was 41.8 ± 6.5 years, mean height was 170.3 ± 5.9 cm, and mean weight was 68.5 ± 9.7 kg. This study was approved by the ethics committee, and all of the volunteers provided written, informed consent prior to participation.

Each volunteer was asked to perform squatting, kneeling, and sitting cross-legged (cross-leg) motions. The activities were performed under fluoroscopic surveillance in the sagittal plane. Sequential knee flexion was recorded as digital X-ray images (1024 × 1024 × 12 bits/pixel, 7.5-Hz serial spot images as a DICOM file) using a 17-inch flat panel detector system (C-vision Safire L; Shimadzu, Kyoto, Japan). On this system, acquired images were nondistorted and clear compared with the Image Intensifier system (Shimadzu). In addition, all images were processed by dynamic range compression, enabling edge-enhanced images. To estimate spatial position and orientation of the knee, a 2-dimensional/3-dimensional (2D/3D) registration technique was used [17, 18]. This technique is based on a contour-based registration algorithm using single-view fluoroscopic images and 3D computer-aided design (CAD) models. Three-D bone models were created from computed tomography (CT) and used for CAD models. The estimation accuracy of relative motion between 3D bone models was ≤ 1° in rotation and ≤ 1 mm in translation [19]. A local coordinate system at the bone model was produced according to previous studies [19].

We decided the femoral, tibial and fibular attachment areas of the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), deep medial collateral ligament (dMCL), superficial medial collateral ligament (sMCL) and lateral collateral ligament (LCL) according to the osseous landmark and magnetic resonance imaging (MRI) [8, 10, 20–28]. The accuracy of the attachment area is 0.7 ± 0.1 mm [28]. The collateral ligaments were each evenly divided into 3 portions (anterior (a), middle (m), and posterior (p)) [8, 10]. The direct distance from the femoral attachment to the tibial or fibular attachment was measured as the ligament length (L) using software (MATLAB, MathWorks, Natick, MA, USA). The ligament length at 0° of knee flexion during squatting was defined as the reference ligament length (L ref). The length change ($\mathcal{e}$) was calculated using an engineering length change formula (i.e. $\mathcal{e} = (L - L\ ref) / L\ ref \times 100$).

Extension relative to the basic ligament length was denoted as positive, and shortening was denoted as negative (Video 1).

All data are expressed as means ± standard deviations (SD). Two-way analysis of variance (ANOVA) and post hoc pair-wise comparison (Bonferroni test) were used to analyse differences in the length change of each ligament among squatting, kneeling, and cross-leg motions. Values of $p < .05$ were considered significant.

Results

1.1. ACL

During squatting, the ACL shortened gradually up to an average of -30.15% ± 4.8% from 0° to 120° with knee flexion. From 120° to 150° with flexion, it extended an average of up to -12.85% ± 7.9%. During kneeling, the ACL did not change significantly from 100° to 130° with flexion. From 130° to 150° with flexion, it extended from − 38.8% ± 4.2% to -31.9% ± 6.3%. During cross-leg motion, the ACL shortened gradually on average from 3.7% ± 6.2% to -36.9% ± 4.3% from 0° to 110° with flexion. From 110° to 150° with flexion, it extended an average of up to -24.9% ± 6.3%.

The length change of the ACL during squatting was smaller than that during cross-leg motion from 20° to 90° with flexion (Fig. 1).

1.2. PCL

The PCL extended gradually with flexion up to 37.6% ± 10.3% during squatting, 43.5% ± 18.8% during kneeling, and 37.9% ± 21.6% during cross-leg motion. Among the 3 deep bending activities, there was no significant difference (Fig. 1).

1.3. MCL

Regarding dMCL, adMCL, and mdMCL extended from 0° to 120° (adMCL 42.6% ± 21.4%, 45.5% ± 20.2%, and 39.5% ± 18.8% during squatting, kneeling, and cross-leg motion, respectively; mdMCL 28.9% ± 21.0%, 30.0% ± 19.0%, and 21.5% ± 18.1% during squatting, kneeling, and cross-leg motion, respectively). From 120° to 150°, adMCL shortened 3.7% ± 19.3%, 3.1% ± 4.7%, and 16.6% ± 12.1%, during squatting, kneeling, and cross-leg motion, respectively, and mdMCL shortened 5.95 ± 18.1%, 2.0% ± 4.6%, and 15.2% ± 11.4% during squatting, kneeling, and cross-leg motion, respectively. Regarding sMCL, asMCL extended 10.1% ± 7.2% during squatting, 9.5% ± 7.1% during kneeling, and 9.2% ± 7.9% during cross-leg motion from 0° to 100° with flexion. From 100° to 150°, they shortened 5.6% ± 8.1%, 5.1% ± 2.6% and 11.3% ± 5.4% during squatting, kneeling, and cross-leg motion, respectively. There were no significant differences in msMCL, psMCL, and pdMCL.

Among the 3 deep bending activities, there were no significant differences in both dMCL and sMCL (Figs. 2 and 3).

1.4. LCL

aLCL extended with flexion (up to 13.7% ± 25.2% during squatting, 12.7% ± 16.7% during kneeling, and 23.7% ± 22.7% during cross-leg motion). On the other hand, there were no significant differences in mLCL and pLCL.

Among the 3 deep bending activities, there were no significant differences (Fig. 4).

Discussion

As far as we know, this is the first study to evaluate in vivo length change of ligaments of the knees with different motions. The ACL was shorter during cross-leg motion than during squatting in mid-flexion. This fact suggested that the ACL is looser during cross-leg motion than during squatting. In other words, the ACL might be easy to affect by differences in flexion motions. Hence, ACL-preserved TKA might be able to reproduce this variation of ACL length change. On the other hand, regarding length changes of the PCL, MCL, and LCL, there were no significant difference among the 3 motions. This suggested that the length changes of PCL, MCL, and LCL do not change even though the high-flexion motions are different. In addition, the ACL might be the most easily affected ligament of the knee in mid-flexion. In high flexion, the length change of the ACL was also not significantly different among the 3 motions. This suggested that any length changes of the ligaments do not change even though the flexion motions are different in high flexion. Therefore, regarding TKA, various motions might be permitted in high flexion in terms of ligament balance.

From early flexion to mid-flexion, the ACL shortened with flexion. On the other hand, it extended slightly during high flexion. These tendencies were similar among the 3 motions. Additionally, the length change pattern with flexion was similar to that seen in previous in vivo studies using transducers [2, 3]. However, the length change of previous studies was less than 10%, while the length changes in the present study were more than 30%. This suggested that the length change of the ACL is different depending on the method of analysis.

The PCL extended with flexion in the present study. Previous studies that investigated in vivo length change of the PCL using static methods also indicated the same pattern, including the absolute values [4, 29, 30]. This fact suggested that the PCL is commonly affected in high flexion, and the length change during dynamic motion was similar to that during static motion.

Regarding the MCL, adMCL, mdMCL, and asMCL extended from early flexion to mid-flexion. This suggested that the anterior portion of the MCL is easily affected in mid-flexion. Furthermore, the deep layer of the MCL might be easily affected in mid-flexion, because two thirds of the portion extended. During TKA for varus knee, we usually release the MCL to modify the soft tissue balance. Releasing the anterior and deeper layers of the MCL might be effective to modify mid-flexion balance.

Regarding the LCL, the anterior portion extended with flexion. This suggested that the anterior portion could be affected in the lateral soft tissue balance, especially in high flexion.

Several limitations of this study need to be discussed. First, the present study only analysed Japanese male subjects. Female subjects or other races might display different length changes. Second, the number of volunteers involved was small. Therefore, the present results might not be generalizable to the general population. Third, only normal knees were evaluated. The length changes to ligaments of osteoarthritis knees and knees after TKA might be different from those of normal knees. Therefore, we will investigate the length changes to ligaments of their knees in our next study. In conclusion, the ACL was shorter during cross-leg motion than during squatting in mid-flexion. This suggests that the ACL is looser during cross-leg motion than during squatting. On the other hand, the length changes of the PCL, MCL, and LCL did not change even though the high-flexion motions were different.

Abbreviations

TKA: Total knee Arthroplasty; 2D/3D:2-dimensional/3-dimensional; CAD:Computer-aided design; CT:Computed tomography; ACL:Anterior cruciate ligament; PCL:Posterior cruciate ligament; dMCL:Deep medial collateral ligament; sMCL:Superficial medial collateral ligament; LCL:Lateral collateral ligament; MRI:Magnetic resonance imaging; a:Anterior; m:Middle; p:Posterior; L:Ligament length; L ref:Reference ligament length; SD:Standard deviations; ANOVA:Analysis of variance

Declarations

Ethics approval and consent to participate

This study was approved by Osaka University ethics committee (Number 13106).

Consent for publication

All of the volunteers in this study provided written, informed consent prior to participation.

Availability of data and materials

The datasets analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

KKand TTdesigned the study and the initialdraft of the manuscript. KK, TT, andTY contributed to analysis of the kinematic data. ST, KS and TT contributed to analysisa data and manuscript preparation.All other authors have contributed to datacollection and interpretation, and critically reviewed the manuscript. The finalversion of the manuscript was approved by all authors.

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Not applicable

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Figures

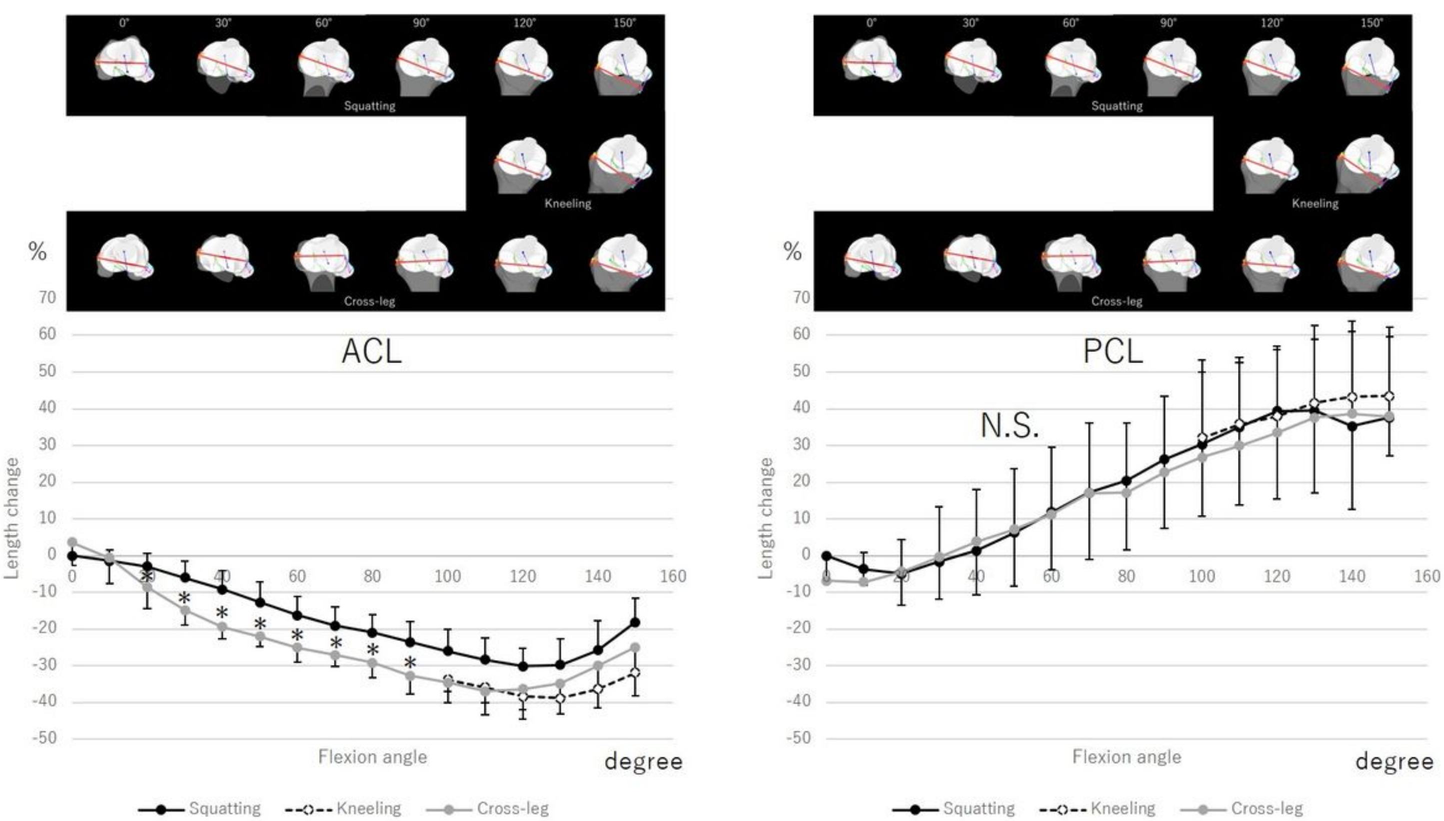

Figure 1

The length change of anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) during squatting, kneeling and cross-leg. Red line of the upper table indicates the surgical epicondyle line. *: Significant differences between squatting and cross-leg (p < 0.05)

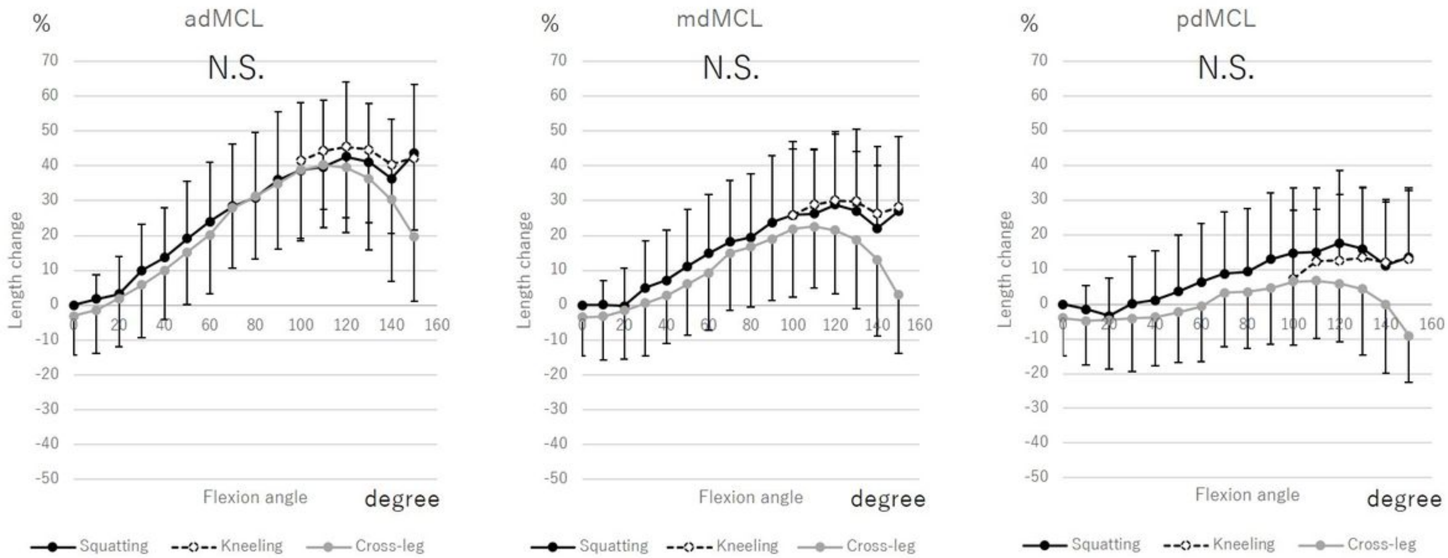

Figure 2

The length change of deep medial collateral ligament (dMCL) during squatting, kneeling and cross-leg. The length change was calculated as the length change rate from the ligament length at 0° of knee flexion during squatting. N.S.:Not significant

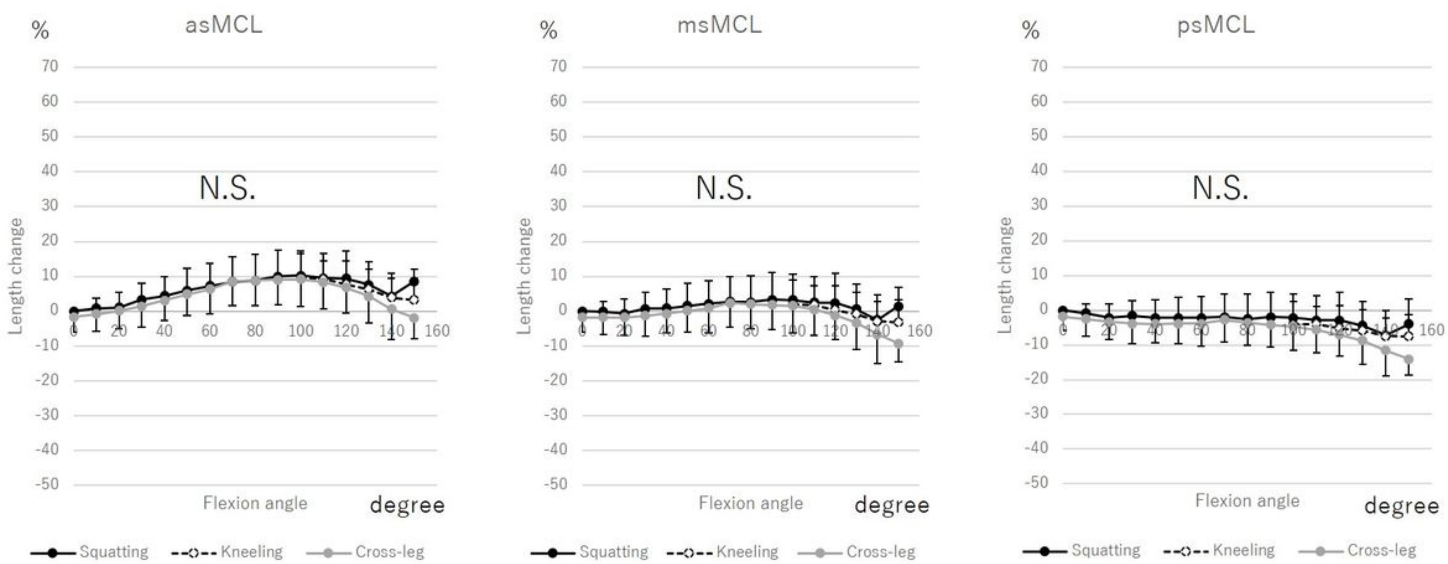

Figure 3

The length change of superficial medial collateral ligament (sMCL) during squatting, kneeling and cross-leg. The length change was calculated as the length change rate from the ligament length at 0° of knee flexion during squatting. N.S.:Not significant

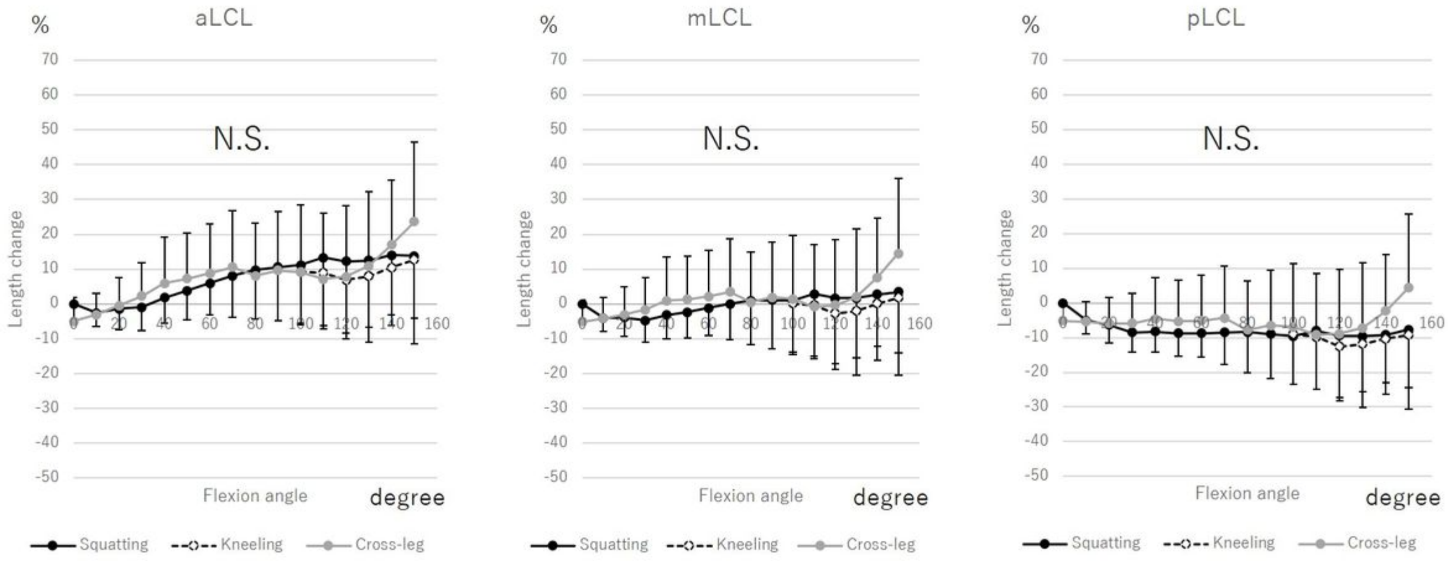

Figure 4

The length change of lateral collateral ligament (LCL) during squatting, kneeling and cross-leg. The length change was calculated as the length change rate from the ligament length at 0° of knee flexion during squatting. N.S.: Not significant

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Video1.mp4