Ligamentous constraint of the first carpometacarpal joint

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Abstract

To examine the role of the ligaments in maintaining stability of the first carpometacarpal (CMC) joint, a sequential ligament sectioning study of sixteen specimens was performed. While a small compressive force was maintained, loads were applied to displace each specimen in four directions – volar, dorsal, radial, and ulnar. Translations of the specimen in both dorsal-volar and radial-ulnar axes were measured. Initially, the tests were conducted with the specimen intact. These tests were then repeated following sectioning of the CMC anterior oblique ligament (AOL), ulnar collateral ligament (UCL), intermetacarpal ligament (IML) and dorsal radial ligament (DRL). The first CMC joint translation was increased in the absence of IML and DRL ($p<0.05$). Both IML and DRL were important in constraining the first CMC joint translation against external applied loads. Potential applications of these findings include the treatment of joint hypermobility and the reduction or delay of onset or progression of first CMC joint osteoarthritis.

Keywords: first carpometacarpal joint, sequential ligament sectioning, anterior oblique ligament, ulnar collateral ligament, intermetacarpal ligament, dorsal radial ligament

1 Introduction

The shallow biconcave-convex saddle shape of the first carpometacarpal (CMC) joint articulating surface provides little bony stability (Ladd et al., 2013); the joint relies heavily on its surrounding ligaments, as passive stabiliser structures, to prevent subluxation. Joint hypermobility and subluxation have been thought to be one of the causes of first CMC joint osteoarthritis (Jonsson et al., 1996, Freedman et al., 2000, Lane and Henley, 2001, Hunter et al., 2005, Lin et al., 2014).

The anterior oblique ligament (AOL) (Pellegrini, 1991, Pellegrini et al., 1993, Imaeda et al., 1994), intermetacarpal ligament (IML) (Pagalidis et al., 1981) and dorsal radial ligament (DRL) (Strauch et al., 1994, Najima et al., 1997, Van Brenk et al., 1998, Bettinger et al., 1999, Bettinger et al., 2000, Ladd et al., 2012) have been considered as candidates for the primary passive stabiliser of the first CMC joint. It is important to know which ligament is the primary stabiliser because if the function of this ligament deteriorates due to, for example, trauma, corrective measures that replicate the function of this ligament can be conducted. Partial or full ligament rupture may cause first CMC joint subluxation because the ligaments can no longer resist loads that try to destabilise the joint (Neumann and Bielefeld, 2003). Lamas Gomez et al. (2015) observed that out of 25 specimens in a cadaveric study, isolated DRL rupture occurred most frequently (40%), followed by AOL rupture (28%). In addition, combinations of tears in IML and DRL (16%) were also observed.

Due to its location near the joint centre, the roles of the AOL are to prevent volar first metacarpal subluxation and to act as the pivot point for internal rotation of the first metacarpal during opposition (Bettinger et al., 1999). The ulnar collateral ligament (UCL) is an extracapsular ligament, with obliquely oriented fibres. Lying ulnar to the AOL (Zhang et al., 2013) it helps to complement the function of the AOL in stabilising the volar aspect of the first CMC joint (Rawat et al., 2016). In a ligament transection study, Colman et al. (2007) determined that the DRL is more important than the AOL in stabilising the first CMC joint during most joint motions. The superiority of the DRL over AOL in stiffness (D'Agostino et al., 2014) and thickness (Ladd et al., 2012, D'Agostino et al., 2014) have made the DRL the most likely candidate for the ligament that is most effective in providing stability and preventing subluxation of the first CMC joint.

Regardless of which ligaments are the best candidates to be the main stabiliser of the joint, laxity can happen to any of these ligaments. It is not known how isolated or combined disruption of the surrounding ligaments alters the function of the joint. Deterioration in the function of the ligaments requires a complex surgical procedure to repair, such as ligament reconstruction, where the anatomy will be modified. It is important to understand how the ligaments work individually or collectively in maintaining the stability of the joint because this information can be used to design corrective measures that require less modification or remove the need to modify the anatomy of the joint. Since the joint has little bony stability and requires the surrounding ligaments to prevent subluxation, it is still not clear how the ligaments react to loads that try to displace the joint in different directions. Hence, the objective of this study was to determine the effect of ligament disruption on first CMC joint translation in multiple planes. It was hypothesised that the IML and DRL are both important passive stabilisers in resisting external forces that try to displace the first CMC joint.

2 Methods

2.1 Specimens

Sixteen fresh-frozen cadaveric mid-forearms through fingertip specimens, consisting of 8 male and 8 female (mean age = 52.4±11.7 years, right hand side = 9, left hand side = 7, ten bilateral, six unilateral) and their computed tomography (CT) images were used in this study. With an alpha = 0.05 and power = 0.80, a sample size of fourteen specimens was needed; hence the sixteen specimens used in this in vitro experimental study were satisfactory to achieve the objective. Ethical approval for the use of these specimens and their CT images was obtained from the Tissue Management Committee of the Imperial College Healthcare Tissue Bank according to the Human Tissue Act. All specimens used in this study were donated with written informed consent for use in medical research. Donors were relatively young, no osteophyte formation was observed on the CT images, and all ligaments appeared healthy and fully intact upon visual inspection. The CT images were segmented with semi-automatic segmentation in MIMICS (v.17, Materialise, Belgium) and smoothing of the surfaces was performed in Geomagic v. 12 (3D Systems, Research Triangle Park, NC, United States) to obtain 3D meshes of the first metacarpal, second metacarpal, trapezium and trapezoid.

2.2 Specimen preparation

2.2.1 Dissection

The first metacarpal, second metacarpal, trapezium and trapezoid were dissected from each specimen without violating the first CMC joint capsule. The second metacarpal and trapezoid were included because the intermetacarpal ligament (IML) links the first and second metacarpal, while the trapezoid prevents the second metacarpal from collapse. All specimens were thawed 24 hours prior to the experiment and each dissection was done by a single hand surgeon. The distal half of the second metacarpal was cut to facilitate specimen preparation.

2.2.2 Specimen alignment

The first CMC joint was tested in a standardised neutral orientation. Based on the recommendations from the International Society of Biomechanics, the neutral posture of the first CMC joint is achieved when the proximal (trapezium) and distal (first metacarpal) segmental coordinate systems are aligned (Wu et al., 2005). To construct the segmental coordinate systems for both the first metacarpal and trapezium on the specimens, access to the joint surfaces of these two bones was required; however, this was not possible, as the joint capsule of the first CMC joint had to be preserved.

The neutral posture of the first CMC joint 3D mesh was achieved by the construction of the local coordinate systems of the first metacarpal and trapezium 3D meshes in 3-Matic (Materialise, Leuven, Belgium). The aligned 3D meshes were exported to computer-aided drafting software, SolidWorks 2016 (Solidworks Corporation, Concord, USA), where they were used to design specimen-specific alignment moulds (see Figure S1 in the supplementary material). The specimen-specific alignment moulds were 3D printed (Ultimaker 3 Extended, Ultimaker B.V., Geldermalsen, Netherlands) and used to orientate each specimen in its neutral posture. Two moulds were required; one to orientate the first metacarpal and the other to orientate the trapezium. The centres of the two moulds were aligned with the centre of the 3D mesh. The mould that secured the trapezium-trapezoid-second metacarpal bones was placed in a fixture made from aluminium (the lower pot) and the mould that secured the distal part of the first metacarpal was placed in a second aluminium fixture (the upper pot; Figure 1). By using a custom-made connector, the aluminium upper pot was attached to a dual-axis materials testing machine (Instron 8874, Instron Corporation, England).

2.3 Customised testing jig

A customised experimental jig was designed and fabricated to displace the specimen by means of external loads and to measure the resultant translation of the first CMC joint. This jig was comprised of three parts: ball table, actuator and sensors (Figure 1). The complete unit was placed on the base of the materials testing machine, which was equipped with a load cell capable of measuring loads up to 1 kN (resolution of 0.001 N) and 25 Nm (resolution of 0.001 Nm).

The ball table acted as the base on which the specimen could rotate and translate. Twenty-five stainless steel ball transfer units (MSP14SS; OMNITRACK, Stroud, UK) were secured to an aluminium base to allow three degrees of freedom. The ball transfer units were spaced in a 5 x 5 grid with 30 mm spacing from centre to centre. This supported the specimen with a minimum of three ball transfer units at all times, while minimising any frictional forces between the lower pot and the base.

A linear electromechanical actuator (Minimech 32, 100mm stroke length; SMS Machine Automation, Barnsley, UK) with a servomotor (SM23165D; Animatics Corp., Milpitas, USA) was installed to apply external loads to the specimens with the purpose of producing subluxation of the first CMC joint. The servomotor was controlled in real time by a proportional integral derivative (PID) controller built in LabVIEW (ver. 2013 SP 1, National Instruments, Austin, USA) (Shah and Kedgley, 2016).

A load cell (DBBSMM, 25 kgf; Applied Measurements Ltd., Berkshire, UK) was attached in series with the linear electromechanical actuator to measure the load applied to the specimen. It also served as the feedback to the PID controller, thus enabling the desired external load to be applied to the specimen.

Two linear variable differential transformers (LVDTs; Figure 1) (Unipolar (DC) output, 30 mm measurement range; Solartron Metrology, West Sussex, UK) were used to quantify the translation of the first CMC joint, measured between the centre of the articulating surface of the trapezium and the centre of the articulating surface of the first metacarpal. The translation of the lower pot was measured in two axes: the dorsal-volar axis and ulnar-radial axis (see Figure S2 in the supplementary material). The LVDTs quantified the position of the trapezium relative to the first metacarpal. However, in accordance with convention from the literature, all applied loads and resulting translations were expressed as the first metacarpal relative to the trapezium (Colman et al., 2007).

2.4 Sequential ligament sectioning

2.4.1 Loading protocol

A 10 N compressive load was applied to the distal end of the first metacarpal to ensure the articulating surfaces of the first CMC joint were always in contact during testing. External loads were applied by the linear actuator to the lower pot to displace the first CMC joint in four different directions, in the following sequence: volar, dorsal, radial and ulnar. The external load applied to the specimen began at 10 N and increased in increments of 10 N. The maximum external load was defined as the external load that could be applied to the lower pot while still maintaining full contact with the ball table (Figure 2).

2.4.2 Experiment

Joint translations in the intact condition were taken as the baseline values of translation of the first CMC joint. Four ligaments were involved in the sequential ligament sectioning experiment: AOL, UCL, IML, and DRL. They were sectioned in the aforementioned sequence. The baseline translations obtained from the intact state were subtracted from those obtained at each stage of the sectioning experiment.

2.5 Statistical analysis

Changes in translations of the first loaded CMC joint after ligament disruption were compared in the four different directions (IBM SPSS Statistics, ver. 25: IBM Corp., Armonk, USA). Normality tests of the studentised residuals were conducted. If the data passed the normality test, a repeated measures analysis of variance (ANOVA) was performed with a Huynh-Feldt correction, and if not, the non-parametric test equivalent, the Friedman test, was implemented. In this statistical test, ligament transection was the dependent variable, and the direction of the applied external load was the independent variable. If significant interactions with p-values less than 0.05 were observed following either the repeated measures ANOVA or Friedman test, further post-hoc analyses or Wilcoxon signed-rank tests with Bonferroni adjustment were implemented, respectively. Pairwise differences within the groups were present if the post-hoc analysis gave a p-value of less than 0.05 or if the Wilcoxon signed-rank test gave a p-value of less than 0.008.

3 Results

The translations of the first CMC joint caused by the external loads applied to the specimens (see Table S1 in the supplementary material) after the transection of AOL, UCL, IML and DRL are listed in Table 1.

3.1 External load in the volar direction

Change in translation of the joint following sequential ligament sectioning did not differ (p = 0.719, repeated measures ANOVA) with the application of an external load in the volar direction (Figure 3(a)). However, there was a difference in the change in translation of the first CMC joint with respect to the baseline values along the radial-ulnar axis after the ligaments were sequentially transected (p = 0.001, Friedman test). No difference (p > 0.05) was found in the change in ulnar-radial translation of the joint between the transection of the AOL (0.47 ± 1.01 mm ulnarly) and UCL (0.69 ± 1.17 mm ulnarly). After transection of the IML and DRL, the change in joint translation was in the radial direction (0.39 ± 1.32 mm, p = 0.003) and moved further radially following transection of the DRL (0.78± 1.50 mm, p = 0.001).

3.4.2 External load in the dorsal direction

Change in joint translation increased dorsally after the AOL, UCL, IML and DRL were sequentially transected (p = 0.0001, repeated measures ANOVA, Figure 3(b)), with the highest mean translation observed after the transection of DRL (2.23 ± 2.72 mm dorsally). Further post-hoc analysis showed that there were two pairwise differences within this group; these were between AOL and DRL (p = 0.041) and UCL and DRL (p = 0.042).

There was also a difference on the change in translation of the first CMC joint along the ulnar-radial axis as the ligaments were transected (p = 0.002, repeated measures ANOVA). Post-hoc analysis determined two pairwise differences within this group; these were between UCL and IML (p = 0.037) and UCL and DRL (p = 0.027). The first CMC joint translated radially after the AOL and UCL were transected and ulnarly following sectioning of the IML and DRL.

3.4.3 External load in the radial direction

There were differences in the change in translation of the first CMC joint along the ulnar-radial axis after the ligaments were sequentially transected (p = 0.001; Friedman test, Figure 3(c)). These were comprised of pairwise differences between IML and AOL (p = 0.003) and DRL and AOL (p = 0.008). The greatest translation was observed after the transection of the DRL (1.66 ± 2.46 mm).

Translation of the joint in the dorsal-volar direction showed significant differences (p = 0.0001, Friedman test), and further post-hoc tests determined pairwise differences between DRL and AOL (p = 0.005) and DRL and UCL (p = 0.003). When the AOL and UCL were sequentially transected, the first CMC joint translated dorsally; however, this translation changed to the volar direction in response to the further sequential sectioning of the IML and DRL. The start and end locations of the first CMC joint translations, which began in the dorsal-ulnar region following transection of the AOL, processed through the dorsal-radial region with transection of the UCL, and ended in the volar-radial region after transection of the IML and DRL (Figure 3(c)). The highest translation was observed after the transection of the DRL (1.27 ± 1.81 mm volarly).

3.4.4 External load in the ulnar direction

There were no significant differences found in the change in translation of the joint along the ulnar-radial (p = 0.353, repeated measures ANOVA) and dorsal-volar (p = 0.087, Friedman test) directions following sequential sectioning of the four ligaments with external load applied in the ulnar direction.

4 Discussion

In vitro sequential ligament sectioning was done to understand how ligaments surrounding the first CMC joint function against loads that attempt to subluxate the joint. Within the literature, there is debate about which ligament primarily stabilises the joint, the AOL, IML or the DRL. In this in vitro experiment, UCL was also included because it frequently has been observed to be elongated in first CMC joints with osteoarthritis (Lahiji et al., 2015).

The findings of this study agree with previous studies regarding the role of the DRL as the primarily ligamentous stabiliser (Strauch et al., 1994, Najima et al., 1997, Bettinger et al., 1999, Ladd et al., 2012). The role played by the DRL and IML in restraining translation of the first

CMC joint in the direction perpendicular to that of the applied load describes a screw-home mechanism (Edmunds, 2006; Haines, 1994). Another important finding in this study was the complementary action between the IML and DRL in constraining the translation. When the first CMC joint was loaded in volar, dorsal or radial directions, the translation of the joint was greater after sectioning both IML and DRL than the translation after sectioning the AOL and UCL. After sectioning the IML, the first metacarpal was in the same quadrant as when the DRL was transected. However, joint translation increased with the absence of the DRL. This supports the complementary, but secondary role played by the IML in maintaining the stability of the first CMC joint (Lamas Gomez et al., 2015). No ligaments were found to play a role in counteracting the loads that tried to displace the first CMC joint ulnarly. The anatomical orientation between the first and second metacarpals acted as an anatomical constraint that prevented the joint from undergoing ulnar subluxation.

When the first CMC joint was loaded in volar, dorsal or radial directions, the DRL and IML were found to constrain the joint along volar and ulnar-radial directions. Translation was increased in the absence of these two ligaments when the joint was loaded in the volar, dorsal and radial directions. Wu et al. (2015) showed a large dorsal CMC joint force during a pipetting task; this study shows the importance of the presence of DRL and IML not just to prevent dorsal subluxation, but also to stabilise the joint along the ulnar-radial axis under such loads. Due to the dense innervation at the dorsal side of the first CMC joint, as compared to the volar site (Ladd et al., 2012), the DRL may also be important in contributing to proprioception, and hence, dynamic stability of the joint. Further study may be required to understand what role muscles play in providing joint stability or how the other passive stabilising components, such as bone morphology, play their roles in stabilising the joint in the presence of damage to either DRL or IML.

Despite its function to prevent volar subluxation of the first metacarpal (Bettinger et al., 1999), the AOL has been found to be recruited less than the DRL across all motions of the first CMC joint (Halilaj et al., 2015), which may indicate that the ligament is slack in most positions. The AOL slackness might explain the lack of differences in translation of the joint after its sectioning. During internal rotation in thumb opposition tasks, the dorsal base of the first metacarpal acts as a pivot point for rotation (Kawanishi et al., 2018). The strong and thick DRL (D'Agostino et al., 2014) may be required to stabilise the dorsal base of the first metacarpal.

Sectioning of the UCL, which is an extracapsular ligament, resulted in differences in translation of the joint, but their translations showed the complementary action of the UCL and AOL.

During functional activities, such as key pinch, the first metacarpal has been captured performing flexion, internal rotation, and volar translation (Halilaj et al., 2014). When a volar force was applied to the first CMC joint, sectioning of the four ligaments involved in this study caused the first CMC joint to translate towards the volar region. The absence of IML and DRL only significantly increased the translation of the first CMC joint in the ulnar-radial direction, not in the dorsal-volar direction. This may be due to the morphology of the first metacarpal and trapezium. In addition, when a volar force is applied, the convex dorsal region of the first metacarpal articulating surface meets the concave dorsal region of the trapezium articulating surface; thus, this can increase the bony stability by restraining the first metacarpal from translating in the volar direction. Less bony constraint in the ulnar-radial directions might explain the observed increase in translation of the joint in this direction. Further study in understanding the complementary function between the shape of the first metacarpal and trapezium with the ligaments surrounding the joint may be needed, considering the shape variations of these two bones.

In this experimental study, the inter-individual variation in observed translation of the first CMC joint was substantial. As all aspects in the experiment including the transection of the ligaments were controlled to ensure consistency in the data collected, the variation observed in the first CMC joint translation among the samples may indicate the importance of the morphology of the first metacarpal and trapezium in contributing to the overall stability of the joint. The morphological variations of the first metacarpal and trapezium among all the samples used in this study may have contributed to the variation in the first CMC joint translation. In a computational study, Rusli and Kedgley (2019) determined that there is morphological variation of the first metacarpal and trapezium in a healthy population of first CMC joints. However, in this experimental study the relationship between morphological variation of both the first metacarpal and trapezium; and the first CMC joint translation was not determined.

In order to prevent first CMC joint degradation in isolated first CMC joint dislocation, diagnosis of ligamentous injury is important. This is to determine whether a surgical intervention is needed, and if needed, Eaton and Littler’s ligament reconstruction method has been used (Lane and Henley, 2001). However, this method requires large alterations of the anatomical structures which may put the joint at risk of recurrent trauma. A capsuloligamentous repair can be an alternative to treat instability of the first CMC joint (Annappa et al., 2015). Kerkhof et al. (2018) determined that the biomechanics of the first CMC joint treated with imbrication of the DRL are not consistent. However, favourable clinical outcomes have been observed (Kerkhof et al., 2018).

This in vitro experiment had several limitations. The order of the ligament sectioning in this experiment was not varied. The anatomy of the joint and the limited number of specimens that could be used in this experiment did not allow for different configurations of the ligament sectioning test. In addition, as force was controlled, rather than displacement, the restraining force of each ligament could not be determined, and the findings are limited to the sequence of ligament sectioning used in this study. Although two distinct structures within the AOL have been identified previously (Ladd et al., 2012), in this study the AOL was tested as a one ligament structure. This was done to ensure that the ligament did not become dehydrated during the experiment due to the time that it would take to identify and correctly section these two structures, if they existed in all specimens, and the risk of not being able to perform the same testing protocol on all specimens. Muscle forces may also play a role in maintaining the stability of the joint; however, due to the need to access the ligaments, the contribution of tendon and muscle was not considered. During the experiment, the orientations of second metacarpal and trapezoid relative to the first CMC joint were not considered. There is no clear definition of how these two bones are oriented relative to the first CMC joint in a neutral orientation. However, the second metacarpal was carefully fixed such that it did not create tension in the IML.

5 Conclusion

Sequential sectioning of the ligaments surrounding the first CMC joint was performed. Four ligaments were tested in this study: AOL, UCL, IML and DRL. It was determined that the presence of DRL and IML impose constraint on the first CMC joint and prevent subluxation of the joint. However, this is not the case for AOL and UCL. These findings suggest that the disruption of the DRL or combination of both DRL and IML, which have been observed in first CMC joint osteoarthritis patients, may produce instability and subluxation of the joint that may lead to aberrant mobility, causing pain, loss of strength, and functional limitations. The reconstruction of either the IML or DRL can be done to strengthen the passive stability of the first CMC joint.

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Figure Captions

Figure 1: The customised testing rig. A ball table, consisting of an aluminium base and twenty-five ball transfer units, allowed the specimen to translate along dorsal-volar and radial-ulnar axes and rotate. The proximal and distal portions of the specimen were cemented into the upper and lower pots, respectively. The red arrow indicates an external load in the dorsal direction and the orange arrow indicate the direction of the compressive force provided by the materials testing machine. LVDT-1 and LVDT-2 were used to measure the translation of the specimen when subjected to external load.

Figure 2: A moment caused by the applied external load resulted in a loss of contact between the lower pot and the ball table (indicated by θ). Testing was stopped if this was observed.

Figure 3: Translation the first CMC joint due to the application of an external load in the (a) volar, (b) dorsal, and (c) radial directions following transection of the anterior oblique ligament (AOL), ulnar collateral ligament (UCL), intermetacarpal ligament (IML) and dorsal radial ligament (DRL). The circles represent the centre of the articulating surface of the first metacarpal plotted relative to the position of the trapezium after an external load was applied to the specimen. The lines represent the mean translation of the joint. DU – dorsal-ulnar, DR – dorsal-radial, VU – volar-ulnar and VR – volar-radial.

Figure 1

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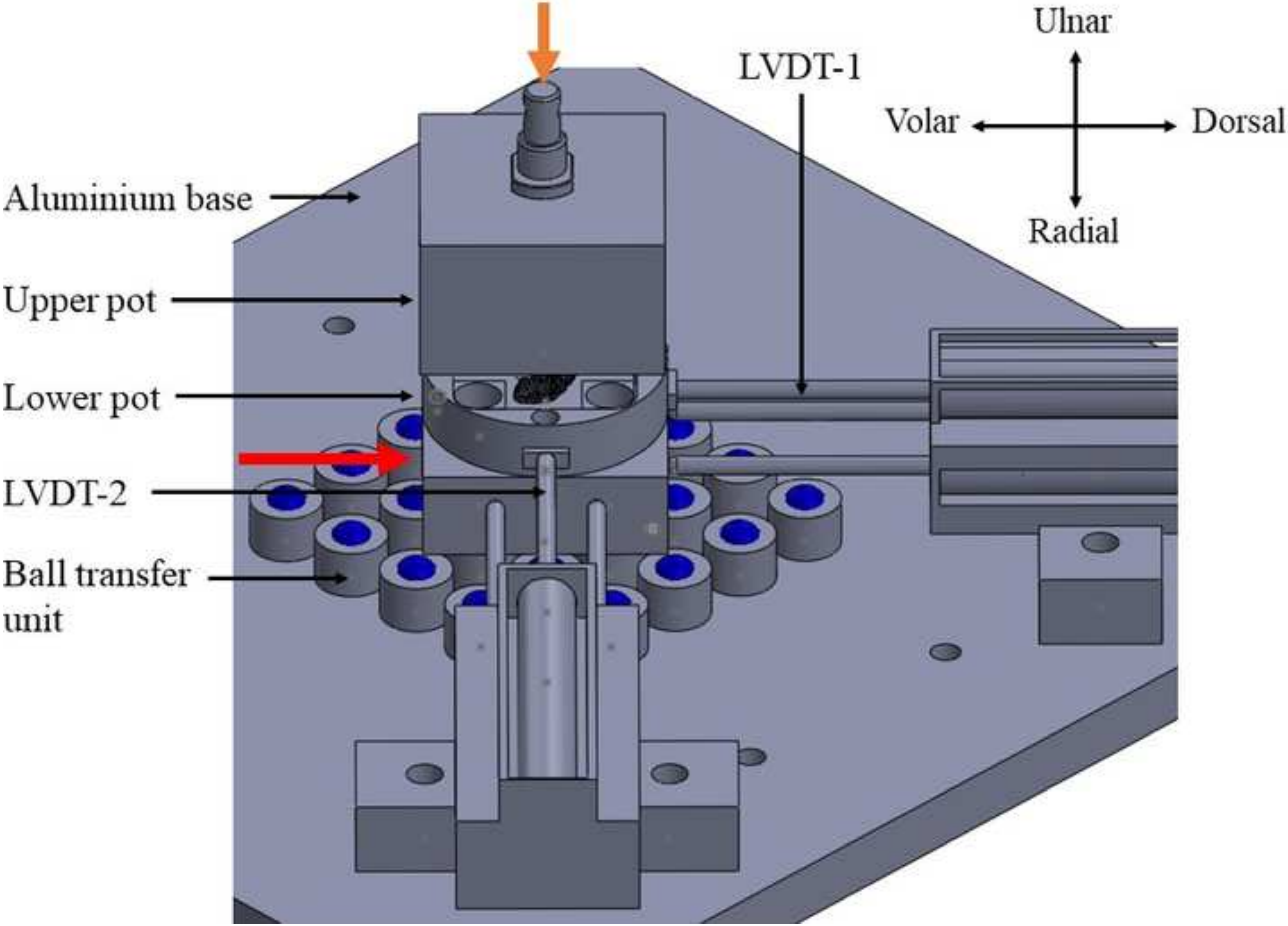

Figure 2

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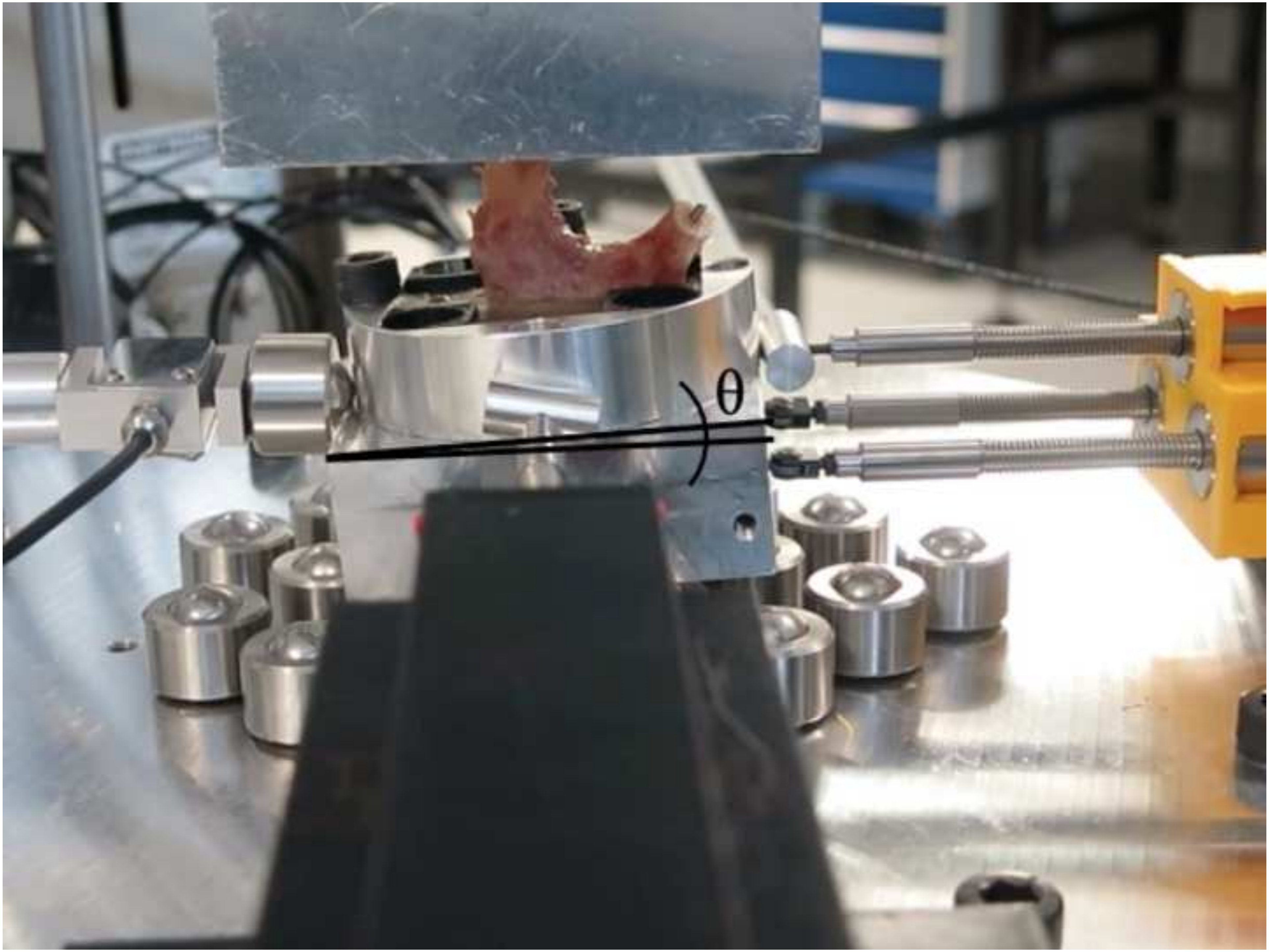

Figure 3

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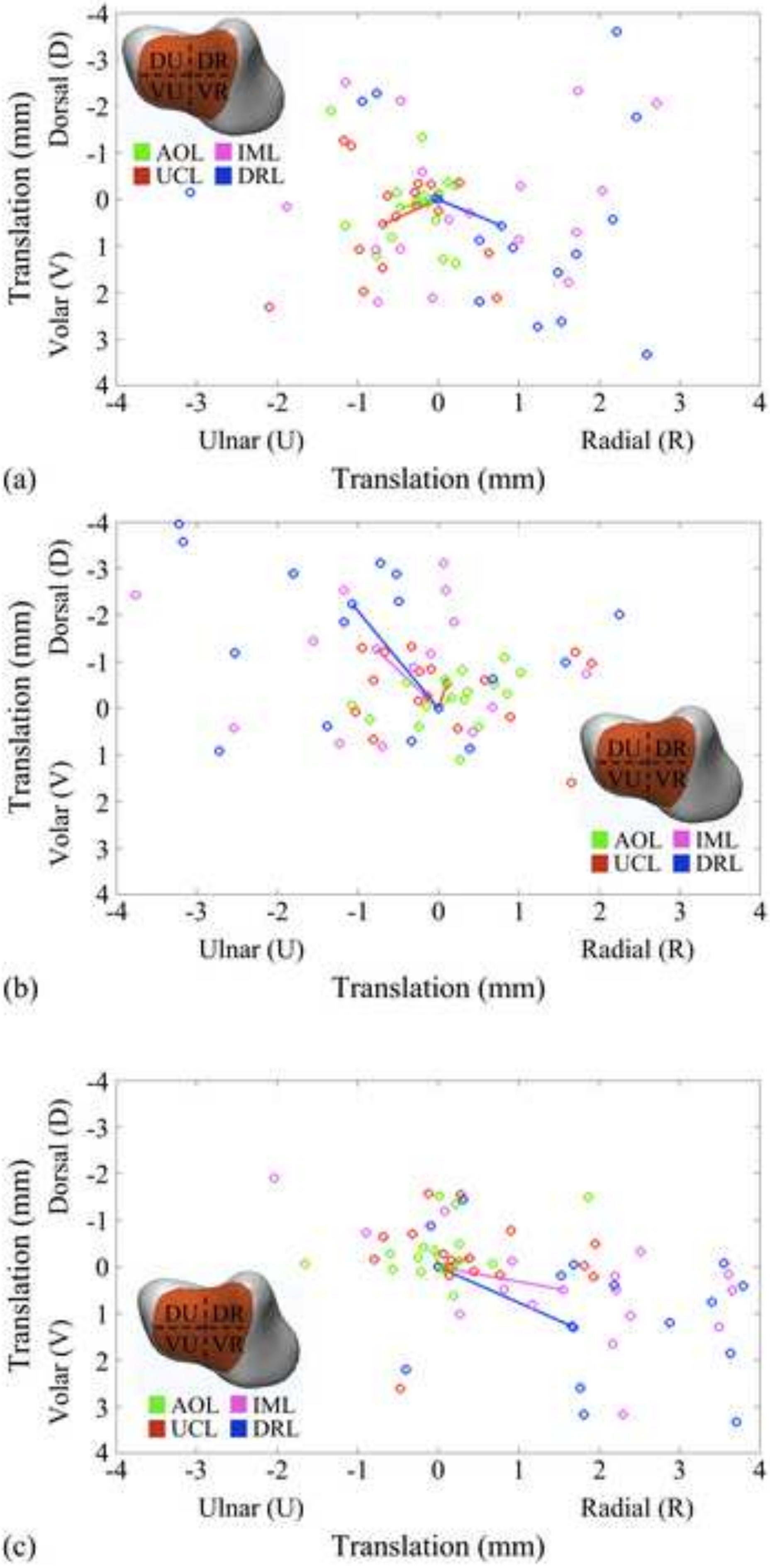

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Table 1: Mean translations (± one standard deviation) of the first carpometacarpal joint due to displacement in the volar, dorsal, radial and ulnar directions after the transection of the anterior oblique ligament (AOL), ulnar collateral ligament (UCL), intermetacarpal ligament (IML) and dorsal radial ligament (DRL). * indicates $p<0.05$ (repeated measure ANOVA) and $p<0.008$ (Friedman test).

Load direction	Experimental condition	Translation (mm)					
		Dorsal - volar axis			Ulnar - radial axis		
Volar	AOL	0.18 (± 1.06)			-0.47 (± 1.01)		
	UCL	0.54 (± 1.72)			-0.69 (± 1.17)	┐*	┐*
	IML	0.30 (± 2.40)			0.39 (± 1.32)	┘	│
	DRL	0.57 (± 2.31)			0.78 (± 1.50)		┘
Dorsal	AOL	-0.24 (± 0.56)		┐*	0.16 (± 0.59)		
	UCL	-0.52 (± 1.08)	┐*	│	0.10 (± 0.97)	┐*	┐*
	IML	-1.27 (± 1.59)	│	│	-0.77 (± 1.43)	┘	│
	DRL	-2.23 (± 2.72)	┘	┘	-1.07 (± 1.78)		┘
Radial	AOL	-0.35 (± 0.67)		┐*	-0.04 (± 0.90)	┐*	┐*
	UCL	-0.19 (± 0.93)	┐*	│	0.39 (± 0.88)	│	│
	IML	0.49 (± 1.42)	│	│	1.55 (± 1.62)	┘	│
	DRL	1.27 (± 1.81)	┘	┘	1.66 (± 2.46)		┘
Ulnar	AOL	0.30 (± 0.76)			-0.30 (± 1.00)		
	UCL	0.43 (± 0.80)			-1.34 (± 1.69)		
	IML	0.15 (± 1.12)			-1.61 (± 1.88)		
	DRL	-0.07 (± 1.20)			-1.86 (± 2.27)		