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Original Article

Motion-plane dependency of the range of dart throw motion and the effects of tendon action due to finger extrinsic muscles during the motion

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Abstract. [Purpose] To clarify the motion-plane dependency of the range of dart throw motion and the effects of tendon action due to long finger flexors and extensors during the motion. [Subjects and Methods] Forty healthy subjects attended the experiment, and the active range of wrist motion in seven motion planes was measured with an originally designed apparatus. [Results] The reliability of the measurement was acceptable. The range of dart throw motion depended on the motion planes, with a maximum at around the motion plane of 45° from the sagittal plane (45° of pronation). The tendon action of long finger muscles was shown in dart throw motion except in 45° of pronation. [Conclusion] Motion-plane dependency of the range of dart throw motion exists in healthy subjects. The absence of tendon action due to finger extrinsic muscles in dart throw motion at 45° might be one of the causes of the advantage of dart throw motion.

Key words: Dart throw motion, ROM, Tendon action

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INTRODUCTION

In most occupational and recreational activities such as hammering, clubbing, or fly fishing, the wrist joint moves along a path from radial extension to ulnar flexion[1, 2)]. This motion is similar to the act of throwing a dart. Palmer et al.[2)] called it dart throw motion (DTM), stating that it was functional and natural. To emphasize the significance of this motion, the International Federation of Societies for Surgery of the Hand defined the DTM plane in 2007 as a plane where wrist functional oblique motion occurs specifically from radial extension to ulnar flexion[3)].

According to a survey[4, 5)] of patients with distal radius fractures, there is a significant correlation between the range of DTM and DASH (Disability of the Arm, Shoulder and Hand) scores; no correlation was seen for ranges measured in an orthogonal anatomical axis (dorsi-palmar flexion or radio-ulnar deviation). In another study, researchers[6)] investigated temporal changes in radiographic findings and wrist joint dynamics of patients with distal radial fractures, and found that changes in the range of DTM were strongly correlated with those in the mobility of the midcarpal joint. Therefore, the range of DTM may be a useful indicator in clinical settings. To our knowledge, no standardized goniometric measurement has been established for this motion.

It is practical to assume a single path of the DTM in clinical settings. Multiple planes of motion, however, occur in daily activities, and the direction of the plane of motion depends on the tasks or tools being used[7, 8)]. Therefore, it would be beneficial, kinesiologically and clinically, to reveal the maximum range of DTM in various motion planes. Crisco et al.[9)]

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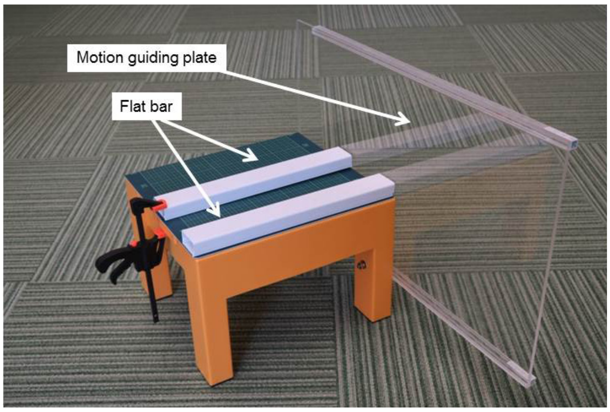

Fig. 1. Measurement platform comprising a horizontal pedestal to place the forearm and an acrylic motion guiding plate. The motion guiding plate is mounted vertically beside the pedestal. On the pedestal are two flat bars where the distal and proximal ends of the forearm are placed to minimize the influence of changes in forearm circumference due to muscle contractions during the measurement.

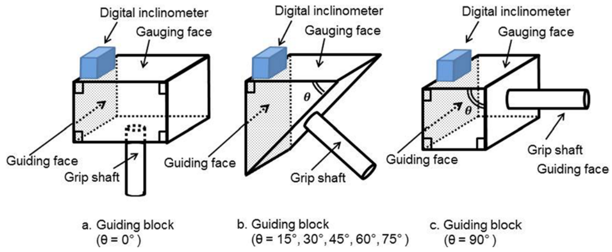

Fig. 2. The seven kinds (θ=0°, 15°, 30°, 45°, 60°, 75°, and 90°) of motion guiding block used for the measurement.

assessed the range of motion of the wrist in 12 planes, including orthogonal anatomical directions (dorsi-palmar flexion and radial-ulnar deviation) in a cadaveric study, and demonstrated that the envelope of the range of motion (ROM) of the wrist was ellipsoidal and the long axis inclined by approximately 30° from the pure flexion-extension axis. However, the extrinsic muscles including the flexor digitorum profundus, flexor digitorum superficialis, or extensor digitorum communis, as well as tendon action were excluded from their study. Gehrmann et al.[10] reported on the effect of the tendon action of the finger extensors on the range of wrist flexion-ulnar deviation. Further analysis of tendon action in DTM is needed.

Joint configuration convention should also be considered. The anatomical reference system, which is defined in the orthogonal anatomical planes, is not defined in accordance with the requirement of the three-dimensional (3-D) kinematics[11]. Some researchers[7, 8, 12, 13] have used 3-D motion analysis systems and calculated the Eular angle (Cardan angles) when analyzing DTM. However, Eular angles need a special instrument and has the problem of rotation sequence dependency or multiple solutions. Although the wrist joint performs 3-D motion, the joint have 2 degrees of freedom of flexion-extension and radio-ulnar deviation without axial rotation. Globographic representation, which Crisco used, is therefore thought to be appropriate for DMT measurements.

In the present study, we designed and fabricated a simple and feasible system for measuring wrist DTM that is based on the principle of globographic representation. The purpose of this study was to reveal i) the motion plane dependency of the range of DTM, ii) the effects of tendon action in DTM, and iii) the reliability of our measurement method for DTM.

SUBJECTS AND METHODS

Forty healthy subjects (20 men and 20 women) aged 18 to 20 years were included in this study. All were right-handed with no history of orthopedic diseases in their right upper limbs or neurological diseases. The mean (range) age, height, and weight of the subjects was 19.3 ± 0.8 years (18–20), 173.5 ± 5.6 cm (167–190), and 69.1 ± 13.2 kg (54–110), respectively, in men, and 19.3 ± 0.6 years (18–20), 160.5 ± 4.1 cm (155–166), and 53.9 ± 5.6 kg (47–60), respectively, in women.

Of the 15 healthy subjects (9 men and 6 women), 11 were included in experiment 1 and participated in the reliability study. The mean (range) age, height, and weight of these subjects was 26.3 ± 10.9 years (18–49), 167.4 ± 6.5 cm (155–178), and 66.1 ± 16.5 kg (51–110), respectively.

Written informed consent was obtained from all the subjects. Ethical approval for the study was granted by the research ethics committees of Showa University (approval No. 379) and Shonan University (approval No. 16-009).

A measurement platform (Fig. 1) and motion guiding blocks (Fig. 2) were originally designed for our experiment. The measurement platform consists of a horizontal pedestal to place the forearm and a transparent acrylic motion guiding plate. The motion guiding plate is mounted vertically beside the pedestal. The pedestal has two flat bars (position adjustable) on which the distal and proximal ends of forearm are placed to minimize the influence of changes in forearm circumference due to muscle contractions during the measurement. The motion guiding block, which determine the motion plane, consists of a wooden right prism (θ=0°, 90°) or a wooden right-angled triangular prism (θ=15°, 30°, 45°, 60°, 75°), and a grip shaft (20 or 45 mm in diameter and 120 mm in length). The weight of each motion guiding block is 80 to 190 g. One of the orthogonal side faces of each block was defined as the motion guiding face, and the other as the gaging face. On the gaging face, a digital inclinometer (BEVEL BOX BB-180, Niigata Seiki, Niigata, Japan) was installed parallel to the motion guiding face. The minimum measurement unit of the inclinometer was 0.1°. Each grip shaft was mounted perpendicularly to and on the center of the grip shaft face. We assumed that an angle θ defines the inclination angle of the forearm (pronation angle) from the sagittal plane and that a thin grip shaft produces a tendon action of the long finger extensor muscles in wrist flexion, and a thick grip shaft produces a tendon action of the long finger flexors in wrist extension. θ=0° means a motion plane of pure radio-ulnar deviation, and θ=90° means that of pure flexion-extension. The neutral position of ROM on each motion plane was defined as a point where the grip shaft is in the frontal plane, perpendicular to forearm. The neutral position in pure flexion-extension was not defined.

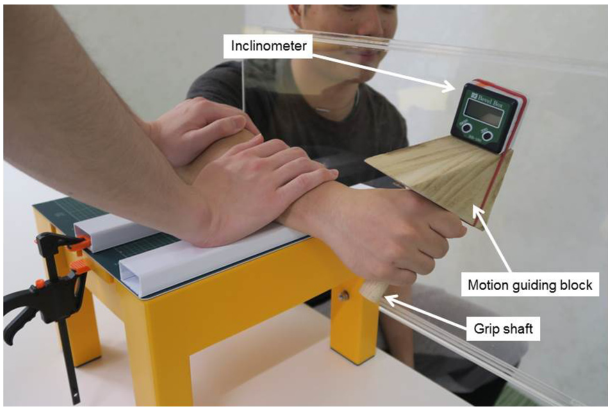

Fig. 3. Testing position of the subjects.

Figure 3 shows the experimental settings. The subjects were seated on a chair, and their right forearm was placed on the pedestal of the measurement platform on the table so that the longitudinal axis of the radius lied parallel to the motion guiding plate. The subject grasped the grip shaft of the motion guiding block naturally and kept the guiding face in contact with the motion guiding plate. The experimenter fixed their forearm manually on the pedestal during the measurement. From this position, active upward (radial-extension) and downward (ulnar-flexion) rotation of the wrist joint in the vertical direction was performed maximally at the wrist joint, keeping contact between the guiding face and plate. Once the gripping position was determined, the subjects were not permitted to change the grip until the end of measurement in each condition.

The maximum tilting angles of the motion guiding block were measured with the inclinometer in upward and downward motions, and the total ranges of motion on each plane were calculated. Measurements were performed twice continuously on each motion plane and grip shaft (7 × 2 = 14 conditions), and the average was used. The measurement order of the motion plane and grip shaft was randomized for each subject. All measurements were performed by the same experimenter (the first author).

The same measurement as above was performed by the similar experimenter in a period of 1 to 7 days for test-retest reliability.

Basic statistics were calculated for the tilting angles of the upward (radial-extension) and downward (ulnar-flexion) rotations, and for the total ROM in each plane. Three-way repeated-measures analysis of variance (ANOVA) was conducted to examine the effect of MOTION PLANE, GRIP SHAFT, and SEX. Paired t-tests were also performed to compare the effect of grip shaft in each condition. Intraclass correlation coefficients (ICC [1, 1]) were used to determine the intra-rater reliability. Statistical calculations were performed with the IBM SPSS Statistics 23 (IBM SPSS Statistics 23, IBM Japan, Tokyo, Japan).

RESULTS

Table 1 shows the test-retest reliability of the measurements in our experiment. The intraclass correlation coefficients demonstrated a relatively higher reliability of the total ROM than those of the radial-extension or ulnar-flexion regardless of grip shaft. The reliability of the total ROM with the thin grip shaft was excellent (0.81−0.94) for all the planes except pure flexion-extension (θ=90°), with a maximum at approximately the middle range of θ, and that with the thick grip shaft (0.69−0.86) was good[14]. The reliability of radial extension was relatively lower than the other conditions.

Table 2 shows the ranges of motion (ROM) of radial-extension and ulnar-flexion, and the total ROM in each condition. Three-way repeated-measures ANOVA (one between-subject and two within-subject factors) for total range showed the main effects of MOTION PLANE ($F_{3.24/122.99}$=50.08: p<0.001), SEX ($F_{1/38}$=4.77: p<0.05), and an interaction of MOTION PLANE × GRIP SHAFT ($F_{4.28/162.57}$=3.62: p<0.01). The main effect of MOTION PLANE indicates that the range of DTM depends on the motion plane. The total ROM had an inverted-U relationship with MOTION PLANE (θ), with a maximum value approximately at a moderate angle θ (see boldface in Table 2). The main effects of SEX indicate that the ROM of women was generally larger than that of men. The interaction of MOTION PLANE × GRIP SHAFT indicates that GRIP SHAFT effects depend on MOTION PLANE. Therefore, paired t-tests were performed to examine the effects of GRIP SHAFT in each condition. In Table 2, the conditions with boxed data show the mean difference between 2 grip sizes (solid lines, p<0.05 and dashed lines, p<0.1). The effects of GRIP SHAFT were indicated at 60° and 75° in all subjects, 75° in men, and 30° in women in the t-tests for total range. The main effect of GRRIP SHAFT ($F_{1/38}$=2.28: p=0.14), the interaction of MOTION PLANE ×SEX ($F_{3.24/122.99}$=0.48: p=0.71), and the interaction of GRIP SHAFT × SEX ($F_{1/38}$=3.15: p=0.08) was not significant.

Radial-extension was relatively smaller than previously reported[10, 13, 17]. Three-way repeated-measures ANOVA on the range of radial extension showed the main effects of MOTION PLANE ($F_{2.04/77.68}$=5.24: p<0.01) and SEX ($F_{1/38}$=13.72:

Table 1. Intra rater reliability of measurement (n=15)

	Angle θ (degree)						
	90	75	60	45	30	15	0
Thin grip shaft							
radial-ext	-	0.83	0.56	0.43	0.44	0.09	0.54
(95% CI)		(0.58 to 0.94)	(0.1 to 0.82)	(−0.08 to 0.76)	(−0.06 to 0.77)	(−0.41 to 0.56)	(0.08 to 0.82)
ulnar-flex	-	0.81	0.62	0.81	0.83	0.73	0.78
(95% CI)		(0.52 to 0.93)	(0.19 to 0.85)	(0.54 to 0.93)	(0.57 to 0.94)	(0.37 to 0.9)	(0.47 to 0.92)
Total	0.55	0.81	0.81	0.84	0.92	0.86	0.82
(95% CI)	(0.08 to 0.82)	(0.53 to 0.93)	(0.54 to 0.93)	(0.83 to 0.98)	(0.78 to 0.97)	(0.64 to 0.95)	(0.55 to 0.94)
Thick grip shaft							
radial-ext	-	0.63	0.74	0.62	0.69	0.76	0.71
(95% CI)		(0.21 to 0.86)	(0.4 to 0.9)	(0.19 to 0.85)	(0.31 to 0.89)	(0.43 to 0.91)	(0.34 to 0.89)
ulnar-flex	-	0.72	0.76	0.54	0.61	0.64	0.76
(95% CI)		(0.37 to 0.9)	(0.43 to 0.91)	(0.07 to 0.82)	(0.18 to 0.85)	(0.23 to 0.86)	(0.43 to 0.91)
Total	0.64	0.84	0.83	0.69	0.73	0.73	0.86
(95% CI)	(0.22 to 0.86)	(0.59 to 0.94)	(0.58 to 0.94)	(0.31 to 0.88)	(0.37 to 0.9)	(0.37 to 0.9)	(0.64 to 0.95)

Values are ICC (1,1). Angle θ is the inclination angle of the motion plane to the sagittal plane. radial-ext: radial extension; ulnar-flex: ulnar flexion; 95% CI: 95% confidential interval; Total: total range of motion.

$p<0.01$). These main effects are similar to the results of total range. The main effect of GRIP SHAFT was not significant ($F_{1/38}$=0.47: p=0.5). Although none of the interactions were significant (MOTION PLANE × GRIP SHAFT [$F_{3.22/122.42}$=1.42: p=0.24], MOTION PLANE × SEX [$F_{2.04/77.68}$=2.17: p=0.12], GRIP SHAFT × SEX [$F_{1/38}$=0.17: p=0.69]), the results of the t-tests for radial extension showed the effects of GRIP SHAFT at 15° and 30° in all subjects and women, respectively. These results demonstrate the existence of tendon action of the long finger flexors.

Three-way repeated-measures ANOVA on the range of ulnar-flexion showed the main effects of MOTION PLANE ($F_{2.24/85.05}$=37.93: p<0.001). The main effects of SEX (F_{138}=0.2: p=0.66), GRIP SHAFT ($F_{1/38}$=2.85: p=0.1), and the interactions were not shown (MOTION PLANE ×GRIP SHAFT [$F_{4.27/162.11}$=31.55: p=0.19], MOTION PLANE × SEX [$F_{2.24/85.05}$=0.66: p=0.53], GRIP SHAFT × SEX [$F_{1/38}$=1.71: p=0.2]). The effects of GRIP SHAFT on ulnar flexion were observed at 60° and 75° in all subjects and at 75° in women in the t-tests. These results suggest the existence of tendon action of long finger extensors.

DISCUSSION

A simple, practical, and reliable method for measuring DTM is needed, but to our knowledge, has not been developed sufficiently. Kasubuchi et al.[15)] created a dedicated device for measuring range of DTF (only 45° pronation) and reported a significant relationship between the range of DTM and activities of daily living score[4, 5)]. The principle of the measurement method, however, was not described in their papers. Furthermore, while it is desirable to postulate a single path of DTM, various motion planes, which depend on movement tasks or tools to be used for the tasks, exist[7, 8)]. Our method was developed to measure the range of DTM in 7 planes, and we found that it had an acceptable except for θ=90°, especially in the total range with the thin grip shaft. Relatively low reliability in radial-extension may be caused by the small range of radial-extension motion. Relatively small radial-extension in this study is related to the convention of 3-D angular representation.

Our apparatus was designed based on the globographic convention[11)] of 3-D joint configuration as is the case with Crisco et al[9)]. We postulated that wrist joint has no movement about the long axis of the wrist joint. Furthermore, motion angles were measured as an inclination of guiding block on the sagittal plane (motion guiding plane), and the neutral angle was the position where the long axis of the grip shaft was in the frontal plane (perpendicular to the forearm). Alternatively, Euler angles were used to represent wrist motion in several studies[8, 10, 13)], in which the neutral joint position was defined as the position of the wrist both in neutral flexion-extension and radial-ulnar deviation, when the long axis of the middle metacarpal bone is parallel to the long axis of the forearm. In this convention, the path of the DTM in several tasks does not pass the neutral position[8)], unlike with our method. Extreme care for joint configuration convention should be taken to compare the results of different studies.

Our method measures the position of an object (guiding block) moved by hand in an external coordinate system, but does not directly measure the joint configuration of the wrist joint. Although this method does not clarify bone-to-bone relation of wrist joint, it would be appropriate for analyzing movement tasks in daily living.

The range of DTM in this study depended on its motion plane, with a maximum at approximately the middle range of

Table 2. Radial-extension, ular-flexion and total range of motion in each condition

	Angle θ (degree)						
	90	75	60	45	30	15	0
All subjects n=40							
Radial-extension							
Thin rod	-	7.9 ± 26.6	16.3 ± 19.8	15.8 ± 16.5	16.5 ± 12.2	13.2 ± 9.9	8.8 ± 9.7
Thick rod	-	10.3 ± 19.1	17.4 ± 14.7	14.3 ± 12.8	12.0 ± 7.6	10.9 ± 7.4	8.3 ± 11.2
p-value		0.473	0.706	0.492	0.008	0.043	0.777
Ulnar-flexion							
Thin rod	-	136.7 ± 26.9	138.1 ± 24.9	143.9 ± 22.7	139.0 ± 25.1	131.1 ± 27.6	115.8 ± 30.0
Thick rod	-	144.8 ± 24.0	143.2 ± 23.0	145.1 ± 21.4	140.4 ± 19.7	133.4 ± 22.8	117.3 ± 21.9
p-value		0.006	0.043	0.674	0.687	0.368	0.591
Total							
Thin rod	**133.0 ± 24.8**	**144.6 ± 24.7**	**154.5 ± 20.8**	**159.6 ± 22.3**	**155.5 ± 24.7**	**144.3 ± 25.8**	**124.6 ± 27.8**
Thick rod	**136.0 ± 31.4**	**155.1 ± 23.8**	**160.6 ± 21.7**	**159.3 ± 20.3**	**152.4 ± 19.6**	**144.3 ± 23.4**	**125.6 ± 24.8**
p-value	0.308	0.001	0.015	0.889	0.252	0.985	0.744
Male n=20							
Radial-extension							
Thin rod	-	−0.2 ± 28.3	10.0 ± 18.8	8.8 ± 13.9	11.9 ± 1.0	8.4 ± 8.7	7.4 ± 8.8
Thick rod	-	2.8 ± 21.1	10.5 ± 13.0	8.5 ± 9.3	9.0 ± 6.9	8.1 ± 7.1	5.4 ± 6.3
p-value		0.566	0.904	0.917	0.222	0.842	0.317
Ulnar-flexion							
Thin rod	-	134.6 ± 28.2	138.4 ± 24.4	142.0 ± 23.7	134.6 ± 24.4	128.6 ± 31.3	110.0 ± 29.7
Thick rod	-	145.0 ± 23.0	144.3 ± 24.3	144.5 ± 21.3	140.4 ± 21.0	132.6 ± 22.8	116.3 ± 23.0
p-value		0.053	0.071	0.444	0.201	0.387	0.1
Total							
Thin rod	124.8 ± 19.4	134.4 ± 19.6	148.4 ± 18.5	150.8 ± 20.2	146.5 ± 21.9	137.0 ± 27.8	117.4 ± 25.6
Thick rod	131.9 ± 26.8	147.8 ± 19.2	154.8 ± 17.4	153.0 ± 18.1	149.4 ± 17.8	140.7 ± 21.3	121.6 ± 24.0
p-value	0.237	0.002	0.084	0.427	0.397	0.367	0.153
Female n=20							
Radial-extension							
Thin rod	-	16.0 ± 22.6	22.6 ± 19.1	22.8 ± 16.3	21.1 ± 12.8	18.0 ± 8.8	10.2 ± 10.6
Thick rod	-	17.8 ± 13.7	24.3 ± 13.2	20.1 ± 13.5	15.1 ± 7.2	13.7 ± 6.8	11.2 ± 14.1
p-value		0.682	0.704	0.413	0.013	0.013	0.778
Ulnar-flexion							
Thin rod	-	138.9 ± 26.2	137.9 ± 26.1	145.7 ± 22.1	143.4 ± 25.6	133.6 ± 23.9	121.6 ± 29.9
Thick rod	-	144.7 ± 25.6	142.2 ± 24.3	145.6 ± 22.1	140.3 ± 18.3	134.2 ± 23.5	118.3 ± 21.2
p-value		0.038	0.279	0.986	0.535	0.793	0.447
Total							
Thin rod	141.1 ± 27.3	154.8 ± 25.5	160.5 ± 21.6	168.5 ± 21.2	164.5 ± 24.4	151.5 ± 22.0	131.8 ± 28.6
Thick rod	142.1 ± 35.4	162.5 ± 25.6	166.4 ± 24.4	165.7 ± 20.9	155.4 ± 21.4	147.9 ± 25.3	129.5 ± 25.5
p-value	0.855	0.113	0.098	0.421	0.031	0.19	0.67

Values are mean ± SD. Angle θ is the inclination angle of the motion plane to the sagittal plane. p-values were calculated in paired t-test. Total: total range of motion; θ=90; palmar flexion and forsiflexion; θ=0; radial and ulnar deviation.

the pronation angle (θ) and an inverted-U relationship with the pronation angle. Crisco et al.[9)] demonstrated similar results to our study in their cadaveric study. The envelope of all possible wrist positions was ellipsoidal-like, whose major axis was inclined at an angle of 63.4° ± 4.4° from the sagittal plane, and the maximal ROM was 178° ± 10.5°. According to the studies that investigated carpal kinematics, the midcarpal joint plays a central role in DTM [16–18)], and the rotational axis of the midcarpal joint penetrates the capitate bone from the navicular tubercle to the hamate bone at an angle of 45° obliquely to the rotational axis of pure flexion-extension in coronal plane view[19, 20)]. This joint structure is thought to be one of the reasons the maximal range of DTM occurred at the middle range of the pronation angle in our study. Another reason, which is the tendon action of multi-joint muscles, is also suggested in our study. The tendon action was observed at an angle θ of 15°, 30°, 60°, and 75°, but not shown at 45°. These results suggest that the tendon action of the long finger flexors and extensors does not exist or is smallest in the middle range of pronation. However, our data is not consistent. The incomplete results of tendon action in the pronation angle θ of 15°, 30°, 60°, and 75° may be due to the small difference between the two grip sizes. Research by Gehrmann et al.[10] supports this conclusion. They investigated the effects of finger constraints on the ROM of wrist circumduction by gripping cylinder rods (diameters, 50, 25, and 0 [fist]) and demonstrated a clear tendon action of the long finger flexors and extensors, especially in ulnar-flexion. A well-modulated manipulation of shaft conditions would have caused more complete results in our study.

As mentioned previously, the advantage of DTM over anatomical wrist ROM (palmar flexion-dorsiflexion and radial-ulnar deviation) is thought to be caused by the carpal joint structure, and/or tendon action of long finger flexor and extensor muscles. This would be useful information to assess and treat of patients with wrist malfunction. Furthermore, the fact that the range of DTM at around the middle range of pronation angle (θ) is maximal and the range of DTM correlates well with activities of daily living score[4, 5] suggests the importance of measuring the range of DTM midrange of the pronation angle in clinical settings.

We acknowledge that this study has several limitations. First, our research was performed in healthy young people and did not include elderly persons or those with disabilities. Clinical feasibility should be examined. Second, measurements were performed with active ROM. Passive ROM may need additional artifices and yield different results. Third, the neutral position of the ROM in the 90° pronation condition cannot be defined theoretically in our method, and the measurement may be inappropriate in the vicinity of the pronation angle.

Conflict of interest

None.

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