2007 IFSSH Committee Report of Wrist Biomechanics Committee: Biomechanics of the So-Called Dart-Throwing Motion of the Wrist

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The dart-throwing motion (DTM) plane can be defined as a plane in which wrist functional oblique motion occurs, specifically from radial extension to ulnar flexion. Most activities of daily living are performed using a DTM. The DTM utilizes the midcarpal joint to a great extent. Scaphotrapezio-trapezoidal anatomy and kinematics may be important factors that cause a DTM to be a more stable and controlled motion. During a DTM, there is less scaphoid and lunate motion than during pure flexion-extension or radioulnar deviation. Clinically, a DTM at the plane approximately 30° to 45° from the sagittal plane allows continued functional wrist motion while minimizing radiocarpal motion when needed for rehabilitation. (J Hand Surg 2007;32A:1447–1453. Copyright © 2007 by the American Society for Surgery of the Hand.)

Key words: Anatomy, biomechanics, dart-throwing motion, midcarpal joint, wrist.

Our vision of carpal kinematics may be obscured by a relatively rigid adherence to the orthogonal sagittal and coronal planes of wrist motion, when in fact most activities of daily life rarely use these planes of motion. It has been historically well known that most activities are performed using an oblique wrist motion from radial deviation-extension to ulnar deviation-flexion, which has often been called the *dart thrower's motion* or the *dart-throwing motion* (DTM). There have been relatively few studies that comprehensively examined DTM, however, and even the definition and terminology of this functional oblique motion is still obscure. Therefore, the purpose of this report is to comprehensively discuss DTM from the viewpoint of anatomy, anthropology, and biomechanics in order to emphasize the importance of DTM.

Terminology

One of the aims of the International Federation of Societies for Surgery of the Hand is to establish and recommend the adoption of certain standards of nomenclature in surgery of the hand. We should use clear and appropriate descriptions and terminology when describing biomechanical methods and results, as well as in the clinical setting. Regarding the description of the extreme positions of DTM, we would like to advocate the usage of *radial extension* instead of *radial deviation-extension* and *ulnar flexion* instead of *ulnar deviation-flexion*. The DTM plane can be defined as a plane in which wrist functional oblique motion occurs, specifically from radial extension to ulnar flexion.

History

Several centuries elapsed from the first formal anatomical description of the carpal by Vesalius[1] in 1543 to the first comprehensive physiological study by Henke in 1859,[2] just before the 1895 discovery of

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the x-ray by Roentgen. Henke, quoted by Linscheid[3] in his review of wrist history, was the first to systematically study carpal motion in cadaver wrists. He noted independent motions at the radiocarpal and midcarpal joints, and he considered motion in the wrist to occur through mutually perpendicular axes passing through the capitate. On the other hand, he noted also that there was no "pure" motion in the joint, and this may be the first suggestion of an oblique axis of wrist joint motion. Roentgen's discovery of the x-ray at the end of 1895 had a deep impact on wrist biomechanics comprehension. During the early years following 1895, many authors tried to understand carpal biomechanics through dynamic radiographs. Destot and Cousin[4–6] focused on the adaptability of the first carpal row (especially the scapholunate unit) during wrist motion and noted that functional wrist motion results from combinations of flexion, extension, abduction, and adduction. Corson[7] concluded in 1897 that the axes of motion of the radiocarpal and midcarpal joints were oblique and confirmed Henke's view that pure flexion-extension and abduction-adduction of the wrist were questionable. He noted that extension aided abduction, whereas flexion aided adduction, and this may be the first formal suggestion of what will later be called DTM. Fick[8] in 1901 constructed a 3-dimensional model of the wrist, which led him to also propose oblique axes for each carpal row that intersected in the capitate.

Almost 50 years elapsed before Bunnell's classic 1944 book was published; Bunnell[9] explains in the chapter about normal wrist motion that "the wrist moves well in the anteroposterior plane but in lateral movements the motion is freer in a plane running slightly dorso-radial and volar-ulnar." In Boyes' 4th edition of Bunnell's book, this assessment is further emphasized: "in normal use, the axis of motion in the wrist is not in a true dorsal volar direction but more from dorso-radial to ulnar volar." Capener[10] published in 1956 his landmark paper about functional wrist motion. Capener quoted Bunnell's description that lateral deviation movements of the wrist are most easily carried out radialward with extension and ulnarward with flexion. Capener noted that in these 2 directions lies the plane of physiological movement and that it corresponds respectively with the action of the radial carpal extensors and the flexor carpi ulnaris. He noted that this oblique movement was well seen in the use of a mallet. He pointed out that in wrist radial deviation-extension (radial extension), there is slight pronation of the forearm; conversely, in wrist ulnar deviation-flexion (ulnar flexion), there is slight supination. He considered that this motion is important in all manual occupations involving a swinging action of the forearm with extension of the elbow joint and strong action of the wrist in an ulnar direction. It is thus seen in the use of most tools of percussion as by sculptors, carpenters, stonemasons, motor mechanics, fly fishermen, tennis players, and orthopedic surgeons.

Fisk[11] described in 1981 that this action is seen in holding a fishing rod to cast a fly, throwing a dart, or conducting an orchestra using a baton. He noted this is the true physiological axis of extension and flexion of the carpus.

Sturzenegger et al[12] reported in 1991 that the results of radioscapholunate arthrodesis showed that the residual plane of motion was restricted to an oblique plane extending from radiodorsal to ulnopalmar. This finding implies that the motion plane of the midcarpal joint is almost identical to the DTM plane. Saffar and Seumaan[13] described in 1994 that there is more mobility and more agility in this oblique plane, as this oblique plane utilizes the midcarpal joint to a great extent. They suggested that more attention should be paid to this plane of motion because the center of rotation of the carpal and of the wrist, the different angles between these bones, and the relative motions of those bones could be more easily understood if studied in this plane.

Contributing Anatomical Factors to DTM

The so-called DTM is the most commonly used plane of wrist rotation in activities of daily living. Furthermore, it is one of the most natural rotations of the wrist that can be done with minimal muscle force. If, in the cadaver, equal amounts of tension are applied to all wrist motor tendons with the forearm horizontal in pronation while the hand is allowed to flex by gravity, there is always an associated ulnar deviation vector added to the obvious flexion tendency. Similarly, when in supination, if the muscle-balanced wrist is allowed to extend by gravity, the natural extension moment generated is always coupled by a variable degree of radial deviation. This oblique plane of physiologic DTM is unique to each individual and depends on a number of anatomical factors.

Joint Geometry Factors

The distal scaphoid surface contains an obliquely oriented ridge, the orientation of which guides scaphotrapezio-trapezoidal (STT) joint motion in a semiconstrained fashion.[14,15] Any motion at the STT joint mostly occurs along that oblique direction of flexion-extension.[16]

The capitate head is not fully spherical but contains a relatively less convex, lateral facet articulating with the medial and distal articular surface of the scaphoid.[14] Such articulation has not a purely sagittal orientation but rather it exhibits an obliquity that mostly facilitates the capitate to flex and extend along the DTM. Any other direction of scaphocapitate (SC) motion would imply loss of congruence between the 2 bones. Fortunately, when this happens, the out-of-plane rotation of the scaphoid adjusts for it and incongruity is avoided.

The scapholunate distal concavity is not fully semispherical. Its oblong shape in the horizontal plane has a major axis that is oriented, once again, along an oblique plane, parallel to the DTM.[17]

The triquetrum-hamate joint has little influence in constraining or providing stability to an obliquely oriented hinge midcarpal joint. The distal scaphoid is located anterolaterally in relation to the capitate, thus making difficult its radial flexion. The distal scaphoid, therefore, would be the "anterolateral malleolus" of the midcarpal joint. The triquetrum, by contrast, does not have a "dorsomedial malleolus" that prevents the hamate towards rotating into ulnar extension. On the other hand, the triquetrum-hamate joint helps in guiding midcarpal rotation. In the semisupinated view of a wrist x-ray, which is almost compatible with an axial view of DTM, the midcarpal joint displays a C-shape outline.[18] The inclination of the distal surface of the triquetrum forms a ulnopalmar part of the C-shape outline. This configuration of the triquetrum-hamate joint favors the smooth shifting of the distal carpal row from radial extension to ulnar flexion and thus playing a role in DTM.

Ligament Factors

The 2 major ligaments connecting the distal scaphoid to the distal row do not originate in the most palmar apex of the scaphoid tuberosity.[19] The SC ligament inserts on the medial side of the scaphoid tuberosity, covered by the floor of the flexor carpi radialis tendon sheath, while the STT ligament inserts on the anterolateral side of the scaphoid tuberosity. The line that connects these 2 insertion sites is perpendicular to the oblique-sagittal ridge of the STT joint, indicating that they function as collateral ligaments of a monoaxial articulation.[17]

There are no vertical ligaments between lunate and capitate. This joint, being highly mobile and unrestricted by soft tissue other than the capsule, participates only passively to DTM.

There are no ligaments connecting the anterolateral and dorsomedial corners of the triquetrum-hamate joint that could act as collateral ligaments stabilizing the midcarpal joint. This medial function is exclusively reserved to the extensor carpi ulnaris tendon, whose dynamic action is the key to avoid other rotations of the capitate different from DTM.

The triquetrum-hamate-capitate (TqHC) ligamentous complex is formed by different ligament bundles connecting the palmar-distal edge of the triquetrum to the hamate and capitate. It originates on the distal rim of the pisotriquetral articular facet and, with a fan-shape configuration, it inserts into the hamate (vertical fibers), the capitate (oblique fibers), and the radius (proximal expansion of the radioscaphocapitate ligament). All these fibers, also known as the ulnar expansion of the arcuate ligament, have little effect in guiding the DTM. In fact, the only ligaments guiding the DTM are the SC and STT ligaments. The main role of the TqHC ligamentous complex is to act as the ultimate stop to the dorsoradial rotation of the distal row at the dorsolateral extreme of DTM.

Muscle Factors

The 2 wrist motor tendons directly involved in generating midcarpal motion along the DTM plane are the flexor carpi ulnaris on the anteromedial side and the extensor carpi radialis brevis and longus (ECRB-L) on the posterolateral side.[20] Aside from this agonist-antagonist action of these 2 muscles, this motion is likely to be guided by 2 other muscles (extensor carpi ulnaris and flexor carpi radialis) whose distal tendon locations at the level of the midcarpal joint coincide with the overall axis of rotation of the DTM. Indeed, for an unrestricted DTM, the muscle tone and tension generated by these 2 structures needs to be symmetrical, one counteracting the other. Any alteration in such synchronicity is likely to result in a rotation different from the one facilitated by the midcarpal joint geometry.

Proprioception Factors

Recent studies using immunohistochemical techniques have disclosed both the STT and SC ligaments to have a scarce number of mechanoreceptors.[21] This indicates that these 2 ligaments are mechanically important in guiding DTM but are poorly involved in triggering a muscle response under external loads. By contrast, the 2 ligaments felt to be ultimate stops of DTM (the palmar TqHC ligamentous complex and the dorsal intercarpal ligament) have been found to be a dense population of receptors. Their action, therefore, needs to be understood more as sensorial important structures triggering the necessary biofeedback loop that would force the flexor carpi ulnaris to contract at the dorsoradial extreme of DTM or the ECRB-L to contract at the other extreme.

Current Biomechanical Knowledge on DTM

Recently, 3-dimensional motion analysis technologies, which enable us to investigate wrist oblique motion 3-dimensionally and quantitatively, have been developed, and detailed information about the functional oblique motion has been revealed. In the last few years, several articles have been devoted to the study of wrist oblique motion even *in vivo*.

Palmer et al[22] first investigated this oblique motion quantitatively in 1985 with the use of a triaxial electrogoniometer. They investigated how much wrist motion was used in performing various activities of daily living. They found that many tasks (eg, hammer a nail, comb hair, wring a washcloth, tie a shoe, pour from pitcher) were performed by moving the wrist from an extended and radially deviated position to a less extended and ulnarly deviated position. They first described this type of oblique motion as a *dart thrower's motion*. This paper suggested how obliquely the DTM plane inclines relative to the sagittal plane. The orientation of this plane varied among activities and even among individuals performing the same activity. According to Figure 9 in the Palmer et al article,[22] we can observe that the path of hammering motion was not a 45° path from radial extension to ulnar flexion but a path from about 40° of extension and about 20° of radial deviation to about 0° of flexion and about 20° of ulnar deviation relative to the radius. This illustrates that a DTM may not only be oblique to the sagittal plane but it also may not pass through neutral flexion-extension and neutral radioulnar deviation.

Li et al[23] investigated *in vivo* coupling between wrist flexion-extension and radioulnar deviation with the use of light-reflective surface markers attached to the forearm and hand. They found the maximal motion boundary of all wrist circumduction cycles was egg-shaped, with maximum extension (64°) at a slight radial deviation of 7° and with maximum flexion at a slight ulnar deviation position (degrees were not shown). The motion boundary was asymmetric with respect to the anatomically defined flexion-extension and radioulnar deviation axes. This suggests that a DTM oblique to the sagittal plane will allow more motion than a pure flexion-extension motion.

Werner et al[24] examined in 1997 how global DTM is apportioned among the individual carpal with the use of an electromagnetic motion measuring system. For an *in vitro* DTM from 20° of extension and 10° of radial deviation to 20° of flexion and 10° of ulnar deviation, they found that while the capitate follows the motion of the third metacarpal, the scaphoid, lunate, and triquetrum showed out-of-plane motions. The proximal row bones did not move in the wrist's DTM plane and moved less than the total wrist motion.

Ishikawa et al[25] investigated the change in percentage contribution of the radiocarpal and midcarpal joints during DTM in cadavers with the use of a magnetic tracking device. For a DTM plane set at an angle of 23° to the sagittal plane, they found the percentage contribution of the radiolunate rotation in radial extension (42%) and in ulnar flexion (39%) were less than those in pure extension (47%) and pure flexion (53%), respectively.

Moritomo et al[16] reported on the kinematics of the STT joint in cadavers with the use of optoelectronic stereocinephotogrammetry motion analysis. They found that the direction of STT motion was from radiodorsal to ulnopalmar during both wrist flexion-extension and radioulnar deviation, and the direction was almost parallel to the plane of the trapezium-trapezoid articulation. Goto et al[26] and Moritomo et al[17,18,27] further investigated *in vivo* kinematics of the midcarpal joint with the use of a noninvasive bone registration technique. They confirmed that isolated STT motion during wrist flexion-extension, radioulnar deviation motion, and DTM were similar, where the angles between STT motion and the sagittal plane were 31°, 43°, and 38°, respectively. They suggested that a DTM may be the most stable and controlled wrist motion and that this could be explained by the anatomy and kinematics of the STT joint. They set the DTM in their experimental protocol as a wrist motion performing a hammering motion, which includes not only radiocarpal motion but also forearm rotation, without intentionally constraining the motion plane at a particular angle relative to the sagittal plane of the radius. They found that their DTM plane was 31° from the sagittal plane[18] and the average contribution of the radiolunate joint to the global wrist motion was 26%.[26] During their DTM, the direction of rotation of the midcarpal and radiocarpal joints were similar and synergistic to each other, which may explain why the

DTM plane is the usual plane of utilization of the wrist.

Werner et al[28] measured *in vitro* scaphoid and lunate motion during 9 variations of wrist motion. The motions ranged from a pure flexion-extension motion to 7 DTMs in which the wrist moved from radial extension to ulnar flexion and finally to a pure radioulnar deviation motion. They demonstrated during intermediate motions of DTM that the scaphoid moved as little as 26% of the global wrist motion and the lunate as little as 22%. In the case of the minimal scaphoid motion, the DTM plane was aligned 45° from the sagittal plane. In the case of the minimal lunate motion, the DTM was aligned 37° from the sagittal plane. This agreed with a suggestion by Marc Garcia-Elias (personal communication, June 2001) that there may be a specific wrist DTM during which there is minimal scaphoid or lunate motion.

Crisco et al[29] measured *in vivo* scaphoid and lunate motion throughout the entire range of wrist motion. They identified a DTM plane approximately 45° from the sagittal plane as a wrist motion during which scaphoid motion approached zero and a plane approximately 30° from the sagittal plane in which there is minimal lunate motion. This finding suggests that specific rehabilitation protocols employing the DTM could be designed to limit radiocarpal motion while providing the benefits of maintaining wrist motion. As suggested by Marc Garcia-Elias and shown by Werner et al[28] and by Crisco et al,[29] however, the specific DTM plane of minimal carpal motion may vary depending on the individual and on which bone needs the least motion.

Upal et al[30] quantified the *in vivo* elongation of the scapholunate interosseous ligament during wrist motion. They demonstrated that there was minimal elongation of the dorsal insertions of the scapholunate interosseous ligament when the wrist moved in a DTM plane that was aligned similar to the plane in which there is minimal lunate motion and that there was minimal elongation of the palmar insertions when the wrist moved in a DTM plane similar to the one in which there is minimal scaphoid motion.

Anthropologic Importance of DTM

There is a compendium of evidence to support the contention that the development of proportionately shorter fingers and other morphologic adaptations of the hand were critical determinants in the ability to use tools and were defining characteristics of the lineage that gave rise to Homo sapiens.[31,32] The ubiquitous presence of DTM in distinctively human activities involving tool use, throwing, and weaponry suggests that its development also may have played an important role in human evolution. Young[33] hypothesized that natural selection "would enhance the anatomical basis for throwing and clubbing." Presumably, improved throwing and clubbing prowess would have provided a survival advantage to early hominid species.[33,34,35] Indeed, the ability to throw rocks or wield a club effectively may have provided an advantage against competitors for food and defense against predators. Developments in the human hand enabled a cylindrical object to be tightly held obliquely in the palm by a modified or squeeze form of the power grip,[36] such that the axis of the tool became collinear with the axis of the forearm in the swing phase of tool use. The effect was to lengthen the tool's lever arm and the force of the tool's impact.[37]

Wolfe et al[37] proposed that forceful and accurate use of a power squeeze grip for clubbing was dependent on the simultaneous facility for a power swing. This power swing is generated by a cocking phase of wrist radial extension and a swing phase of ulnar flexion—that is, DTM. This smooth, stable, and reproducible wrist DTM accelerates the tool, and in clubbing it amplifies the wrist torque generated from the powerful forearm musculature by the added leverage of the tool handle. From a biomechanical perspective, the ability of the wrist to move through a large range of wrist motion while grasping a club greatly increases the impact power that can be delivered with the club. As the upper extremity moves through the swing phase, the 3 aligned primary articulations (wrist, elbow, and shoulder) can contribute to accelerating the club, maximizing its velocity just before impact. The DTM allows the upper extremity to coil into this optimal cocking position and continuously extend during the swing. This coiling and uncoiling minimizes the inertial resistance in the early phases of the swing, which in turn maximizes the final velocity.

Clinical Relevance and Future Investigation on DTM

Preservation of midcarpal function is critical for the DTM. Early midcarpal motion exercise might be permissible after complex surgery of the radiocarpal joint and proximal carpal row for scapholunate ligamentous tears or intra-articular distal radius fractures, provided that rehabilitation protocols could be devised to constrain motion to the DTM plane. In particular cases, the use of an external fixator to bridge only between the proximal carpal row and the radius may facilitate early midcarpal motion exercise. One may need to select a particular plane of DTM, however, to match a patient and the desired carpal bone motion or ligament elongation minimization.

Theoretically, almost full range of the DTM can be achieved after an appropriately aligned radiolunate fusion or radioscapholunate fusion. We therefore recommend a radiocarpal arthrodesis more than a midcarpal arthrodesis such as the STT arthrodesis or the four-corner arthrodesis if the cartilage in the midcarpal joint is intact, in order to preserve midcarpal function. An understanding of the wrist kinematics during the DTM may help in the design of more durable prosthetic implants that more closely mimic normal carpal motion.

In the previous studies of DTM, the pronation-supination motion of the distal radioulnar joint was not taken into consideration. As suggested by Capener,[10] in wrist radial extension, there is slight pronation of the forearm; conversely, in wrist ulnar flexion, there is slight supination. This implies that kinematic studies of DTM should include distal radioulnar joint motion. In the future, we need to investigate wrist motion relative to not the radius but the ulna. Furthermore, anthropologic analysis has shown that the power swing motion of the human upper extremity in which there are 3 aligned primary articulations (wrist, elbow, and shoulder) contributes to accelerating the club and is closely related to DTM. These facts support the importance of investigating DTM globally as a multiple-joint motion that includes the forearm rotation, elbow flexion, and even shoulder motion.

Many wrist investigators consider that the midcarpal joint is functionally more important than the radiocarpal joint because the DTM plane utilizes the midcarpal joint to a greater degree. We should revise our knowledge concerning the functional significance of the midcarpal ligaments from the viewpoint of DTM. Future *in vivo* 3-dimensional kinematic studies for the midcarpal ligaments may help to clarify the functional anatomy of the midcarpal ligaments.

We also need to determine how obliquely the DTM plane inclines relative to the sagittal plane in terms of individual differences. Is there any difference in DTM between column-type and row-type wrists? We suspect that the column-type wrists have a DTM plane almost parallel to the frontal plane, and vice versa for the row-type wrists, but this needs to be investigated.

Sirkett et al hypothesized that the carpal move during the DTM to maximize total contact area in the joint, thereby minimizing contact stress.[38] Such a strategy would minimize the bone mass requirements, thereby minimizing the biological "cost" of creating and maintaining the joint. This agrees with the minimum energy principle, which governs many natural processes.

Motion analysis technologies have been developing considerably from 2-dimensional x-rays to *in vivo* 3-dimensional analysis in the past 100 years. The true real-time compilation of *in vivo* 3-dimensional kinematic data has not yet been reported, however, because of limitations in the speed of image acquisition and concerns for radiation exposure. It is anticipated that, with the development of new technologies, these questions will be answered in the near future.

Summary

1. The DTM plane can be defined as a plane in which wrist functional oblique motion occurs, specifically from radial extension to ulnar flexion. Most activities of daily living are performed using a DTM. The DTM plane may vary between activities and between individuals.
2. The DTM utilizes the midcarpal joint to a great degree. STT anatomy and kinematics may be important factors that cause a DTM to be a more stable and controlled motion.
3. During a DTM, there is less scaphoid and lunate motion than during pure flexion-extension or radioulnar deviation. The amount of scaphoid and lunate rotation relative to the radius during various DTM is highly dependent on the direction of global wrist motion.
4. The wrist motor tendons directly involved in generating DTM are the flexor carpi ulnaris and the ECRB-L. The DTM is likely to be guided by the extensor carpi ulnaris and the flexor carpi radialis, whose distal tendon locations at the level of the midcarpal joint coincide with the overall axis of rotation of the DTM.
5. Physiologically, hammering or clubbing motion is performed using a DTM plane where a greater arc of wrist motion than pure flexion-extension motion is possible. The DTM allows the upper extremity to coil into the optimal cocking position and continuously extend during a power swing. The DTM permits improved clubbing prowess of a cylindrical object.
6. Clinically, a DTM at the plane approximately 30° to 45° from the sagittal plane allows functional wrist motion while minimizing radiocarpal motion when needed for rehabilitation.

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