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Wrist biomechanics and Instability: Wrist dart-throwing motion updated

Introduction

The term “dart-throwing” (DT) motion, or dart-thrower's motion, is used to designate one of the most frequently utilized planes of wrist motion, the one that brings the wrist from a radially deviated-extended position (radial extension) to an ulnarly deviated-flexed position (ulnar flexion).[1] DT motion is particularly prevalent in most occupational, recreational and avocational activities, such as hammering, clubbing or fly fishing.[2-6] In 2007, the IFSSH (International Federation of Societies for Surgery of the Hand) Committee on Wrist Biomechanics published a historical perspective and a summary of the basic principles of DT biomechanics.[1] The purpose of this article is to update that report based on the most recent research published on the kinematics, kinetics, and clinical applications of DT motion.

Carpal kinematics

The wrist is a composite joint. When it moves, a complex interaction and accumulation of motions occur at its different levels. For the wrist to reach its maximal range, all of its joints [radiocarpal (RC), midcarpal (MC) and intercarpal] must collaborate in that rotation. That rule has two exceptions: 1) when the wrist rotates along the DT plane of motion, only the MC joint moves about a proximal row that remains still, and 2) when the wrist rotates along the so-called reversed DT plane of motion (from ulnar extension to radial flexion), motion occurs almost exclusively at the RC joint. From a kinematic point of view, therefore, the wrist can be compared to a universal joint with two axes of motion, one for the RC joint, another for the MC joint, separated by an intercalated segment (the proximal row) aimed at coordinating the two levels of rotation. What follows is a review of the studies that have provided new data in these regards.

Crisco et al.[7] predicted near-zero scaphoid rotation when the wrist rotates along an oblique plane oriented at an angle of 33° to the sagittal plane, while for the lunate to remain still, the wrist needs to move along an oblique plane 20º to the sagittal plane. These values are slightly inferior to the ones reported by Werner et al. who found that, to obtain minimal scaphoid and lunate rotations, the wrist needs to move along motion paths oriented at an angle of 45° and 37° respectively to the sagittal plane.[8] It is important to note, that in both investigations the wrist was mobilized taking the neutral wrist position as a reference (zero degrees on both flexion-extension and radio-ulnar deviation). Indeed, one may bring the hand from radial extension to neutral and continue from neutral to ulnar flexion, following an oblique plane that intercepts both the coronal and sagittal planes at the same time. This, however, is not the most common. More often on actual activities, DT rotation is done along an oblique plane that is parallel to the previous one, but that has an offset toward the dorsal side and does not intercept the coronal and sagittal planes at the zero position[5,9]. When this happens, that DT plane is said to be a "functional" DT plane. By contrast, when the wrist takes an oblique path across the neutral wrist position, the DT plane is said to be a "pure" DT plane. The kinematic differences of mobilizing the wrist along a "pure" or a "functional" DT planes are not fully understood, but certainly the subject deserves specific attention. There are circumstances in which it may be advisable to rehabilitate a wrist by performing repeated rotations along a pure DT plane of motion; in other cases it may be advisable to avoid such commonly used paths. In general, it is admitted that, after certain types of radiocarpal and/or proximal row reconstructions, motion along a pure DT plane can be allowed without concern for disruption or attenuation of the reconstruction, because the proximal row remains relatively still during that particular type of rotation.[10]

There are still many unknowns in regards the kinematics of DT motion. For instance, it is still unclear whether the functional DT plane of motion which is used most commonly in activities of daily living (such as in hammering) is the same as the pure DT plane where scaphoid and lunate motion is minimal. The recent findings regarding the relative contribution of the radiocarpal joint to the overall wrist motion during DT rotation have vary substantially from one author to another [7,8,11-13]. Scaphoid rotation during DT motion has been reported to be as little as 26% and as much as 50% of overall wrist motion, while the range of reported lunate rotations has varied from 22% to 40% of overall wrist motion. While it is convenient to imagine a single plane of motion that enables complex wrist functions, most researchers agree that several DT motion paths of composite radio-ulnar and flexion-extension are likely to contribute to a wide variety of functional activities.

Leventhal et al.[14] examined healthy volunteers with computed tomography (CT) scans, performing a simulated hammering task, using a path of wrist motion from radial extension to ulnar flexion, and found that during a simulated hammering task the rotations of the scaphoid and lunate were not minimal but averaged 40% and 41% respectively of total wrist motion. According to that, radiocarpal motion accounted for 40% of the overall wrist motion, with the remaining 60% occurring at the midcarpal joint. These greater percentages of scaphoid and lunate motion during hammering, as compared to the ones found for pure DT motion with near zero scaphoid and lunate motion, appear to indicate that, indeed, pure DT and functional DT are different wrist motion paths. Furthermore, in that study, the average plane of motion while hammering was oriented 41° from the sagittal plane, and was parallel to the pure DT plane with a substantial offset between the two. From that study we learned that, motions which require a greater range of gripping force, such as hammering, are likely to exhibit greater ranges of scaphoid and lunate motion. In other words, there exist a wide range of DT planes, parallel to the "pure" DT plane, each with its own advantages when it comes to move while grasping or gripping an object.

Crisco et al.[15] demonstrated in the cadaver that mechanical axis of the wrist, and found this not to be aligned with the anatomical sagittal or coronal axes of the hand. The envelope of all possible wrist positions was ellipsoidal in shape and oriented obliquely at a mean angle of 26.6° ± 4.4° to the sagittal plane of motion.[15] It was also noted that the greatest total range of motion, in the direction of radial extension to ulnar flexion, was

142° which was greater than their total range of flexion-extension motion of 129°. This supports the concept that a functional DT facilitates those activities which require greater wrist motion.

Because several DT paths of composite radio-ulnar and flexion-extension are likely to contribute in a variety of functional activities, the term “coupled” wrist motion is emerging as a more inclusive term for describing out-of-plane motion from a kinematic, clinical and rehabilitative perspective[16]. Measuring coupled wrist motion clinically has presented unique challenges. While goniometric measurement of the conventional orthogonal planes of flexion-extension and radio-ulnar deviation has been demonstrated to be accurate and repeatable within 10 degrees,[17] no similar reliability study has been performed for manual measurement of coupled motions or postures. The technique and challenges of measuring coupled motion along the DT plane in a rehabilitation practice were recently outlined by Bugden [18].

The emergence of in vivo three-dimensional motion analysis techniques [markerless bone registration technique using sequential CT or magnetic resonance imaging (MRI)] enabled precise analysis of complex motions of the individual carpal bones in live subjects [7,10,13,14,19-22]. However, we need to be careful in interpreting these results because the technique is limited to a quasi-static analysis of wrist motion and the inability to recreate physiologic rheology conditions of the joint in the 3-dimensional gantry. Additionally, the levels of ionizing radiation limit the use of this technique in general practice. The use of so-called 4-dimensional advanced imaging, whether fluoroscopy, ultra-fast CT scans or MRI, is evolving [23-25] and has already been found useful to study what happens within the carpus when a wrist with a scapholunate dissociation rotates along a DT plane.[25] Garcia-Elias et al reported that, when the scapholunate ligaments were torn, the scaphoid shifted towards the radial styloid considerably more than the lunate, inducing a scapholunate gap. [25] Based on these findings, they did not recommend dart-throwing exercises after scapholunate ligament repair.[25] Video recording of motion can qualitatively demonstrate differences in circumduction arcs between normal and injured wrists or between patients, but cannot yet be utilized currently to provide objective kinematic data.

Recently, unique algorithms for kinematic analysis using applied skin optimal marker sets and measured by multiple simultaneous video cameras have been effectively utilized to accurately quantify normal motion during functional activities.[9,26,27] It is likely that these techniques will further evolve to facilitate accurate upper extremity analysis and reporting in vivo. Brigstock et al [9] using passive reflective markers and 3-dimensional motion analysis in 10 subjects, confirmed in-vivo the use of DT motion during daily activities in both seated (forehand hair combing, backhand hair combing and drinking from a glass) and standing positions (hammering a nail, throwing a ball, pouring from a jug, undoing a button, doing-up a button, and twisting off and on the lid of a jar). They found the mean plane of a measured simulated DT motion to be 44° to the sagittal plane of the forearm, inclined from a position of radial extension to ulnar flexion. They demonstrated that wrist motion approximated the DT motion when hammering a nail, throwing a ball, drinking from a glass, pouring from a jug and twisting off and on the lid of a jar since their planes of motion ranged from 38 to 48 degrees from the sagittal plane and were not significantly different from the simulated dart throw motion plane. Two activities were found to not have a plane of motion similar to a dart throw motion; combing hair or buttoning or undoing a button.

Impact of carpal bone fusions on DT motion

Disorders that affect DT motion include anything that disrupts the coordinated gliding of the radiocarpal or midcarpal joints, including ligament disruption, post-traumatic or degenerative arthritis, inflammatory arthritis, Kienböck's disease, or Preisser's disease. Garg et al [28] examined the relationship between wrist coupling (the amount of flexion-extension per degree of radial-ulnar deviation) and functional performance in patients after midcarpal arthrodesis. They found that altered wrist coupling will result in diminished performance in selected occupational and sporting activities (dart throwing, hammering, pouring, and basketball tasks). Compensations afforded by the elbow and shoulder may influence the performance of certain functional tasks.

Several authors have recently recommended radiocarpal rather than midcarpal fusions (if the cartilage in the midcarpal joint is intact), in order to preserve midcarpal function. Arimitsu et al reported that the midcarpal motions were well preserved after both radio-lunate and radio-scapho-lunate arthrodesis [20]. The postoperative direction of wrist motion in their study was oblique from radiodorsal to ulnopalmar along a DT plane. Additionally, it has been demonstrated that midcarpal and lunotriquetral motion are increased after simulated radio-scapho-lunate fusion [29, 30]. Moritomo et al revealed that capitate motion relative to the scaphoid was essentially uniaxial and that the motion plane was oblique from radiodorsal to ulnopalmar, whereas the direction of capitate motion relative to the lunate had more flexibility and could range between the pure flexion-extension plane and the DT plane [13]. Therefore, the residual motion plane of the capitate after radio-lunate arthrodesis is more flexible than after radio-scapho-lunate arthrodesis.[20] If the scaphoid is fixed to the lunate, the direction of capitate motion relative to the lunate is dominated by the direction of capitate motion relative to the scaphoid and limited to the DT plane.

Distal scaphoidectomy has been developed in order to improve the range of motion after radio-scapho-lunate arthrodesis. [31] There are reports that distal scaphoidectomy also improves fusion rates and lowers the incidence of midcarpal arthritis [31]. However, distal scaphoidectomy could alter the kinematic behavior of the remaining joints with unknown consequences. Since it was suggested that the scaphotrapezium-trapezoid joint is a key anatomical factor that stabilizes and controls DT motion [32], distal scaphoidectomy could abolishes the plane of DT motion and how the wrist moves through an oblique DT motion -like plane of motion. We need long-term surgical outcomes to better elucidate these concerns.

Kamal et al [22] measured the in vivo articulation of the triquetrum-hamate joint as the wrist moves along the DT path. The study suggested that wrist ulnar flexion is constrained by the triquetrum-hamate joint. The concave distal ridge of the hamate guides the triquetrum toward the hook of the hamate until it is fully engaged, which blocks further ulnar flexion of the wrist. This may provide carpal stability while also serving as a rationale for triquetrum excision to increase the range of wrist motion. Pervais[33] postulated that removal of both the triquetrum and distal scaphoid converts the complex midcarpal joint into a simple ball and socket joint, though the kinematics of that condition have not been fully studied. It is possible that the benefit from an increase in midcarpal motion may be offset by the well-established belief that altered kinematics may change load distribution and accelerate degenerative osteoarthritis [34].

Coupling of wrist and forearm rotations

Anderton and Charles [35] tried to quantify the coordination and coupling of wrist and forearm rotations in healthy subjects performing activities of daily living. They reported that flexion of the wrist is often accompanied by ulnar deviation and supination, and extension is often accompanied by radial deviation and pronation. On the contrary, Leventhal et al [14] stated that hammering is performed with limited forearm pronation/supination motion. More study will be needed regarding the coupling of wrist and forearm rotations.

Carpal Ligaments

Tang et al [21] investigated length changes in radiocarpal and midcarpal ligaments of the wrist, in different positions of the DT motion in vivo. They found that from radial extension to ulnar flexion the lengths of volar ligaments (radioscapohocapitate (RSC), long radiolunate (LRL), ulno capitate (UC) and ulnotriquetral (UT)) significantly decreased, whereas the lengths of the dorsal ligaments (dorsal radiocarpal; portion of the dorsal intercarpal ligament inserting on the trapezoid) increased progressively. The ulnolunate ligament and the portion of the dorsal intercarpal ligament inserting on the scaphoid were shortest in the neutral position. They noted that the four ligaments (RSC, LRL, UC and UT) that were tighter in radial extension and more lax in ulnar flexion represented both radial and ulnar stabilizing structures. It may be that more stability is provided in radial extension at the start of a dynamic motion such as hammering and throwing and less is needed or desirable as the wrist moves into ulnar flexion. In addition, biomechanical studies on the UT ligament have shown that its length is maximum during wrist radial extension, thus this ligament is at risk at the extension phase of DT motion, especially with the forearm in supination [21, 36, 37]. Upal et al [10] have shown that scapholunate (SL) interosseous ligament elongation is minimal as the wrist is positioned along the DT path. It is known that the STT and scaphocapitate ligaments are considered as collateral ligaments of the STT joint that stabilize and control DT motion.[38] However, recent studies demonstrate that these ligaments have very few proprioceptive functions—implying that their principal function is mechanical—in contrast to the dorsal intercarpal ligaments and triquetral-hamate-capitate ligaments, which are thought to constrain the end points of DT motion (i.e. “stops”) via their substantial proprioceptive properties [39].

Role of the Muscles

We know that the two wrist motor tendons directly involved in generating swing motion along the DT plane are the flexor carpi ulnaris (FCU) and the extensor carpi radialis brevis and longus (ECRB-L). According to the paper presented by Salva-Coll et al [40], these two muscles together with the abductor pollicis longus (APL) are considered as muscles that supinate the midcarpal joint (midcarpal supinators). Since the ligaments crossing the midcarpal joint (ulnar arm of the arquate ligament, SC ligament and STT ligament) are intact, the supination moment will also be transmitted to the proximal row bones. The authors argued that if all carpal supinator muscles contract while the pronators (extensor carpi ulnaris (ECU), flexor carpi radialis (FCR)) relax, the scaphoid is likely to rotate further into supination, a position in which the dorsal SL ligament is better protected. It is therefore reasonable to assume that, by performing a task along the plane of DT motion under the contraction of the supinator muscles of the midcarpal joint, the SL joint is more stable.

In a cadaver study, according to Werner et al [41] during a DT motion, the mean and peak tendon forces of ECRL and FCU were the greatest compared to the corresponding values of ECU, ECRB, APL and FCR tendon forces. Both the peak and mean FCR forces were shown to be significantly less during the DT motion than during wrist flexion-extension, radioulnar deviation or circumduction motions. On average the peak FCR forces were 24% less while the mean FCR forces were 49% less than during the other motions. Conversely the mean and peak FCU forces were significantly greater during a DT motion compared to the other 3 motions (peak forces 86% greater, mean forces 79% greater). These results indicate that to achieve different desired wrist motions different tendon forces are required. Weak musculature may alter the oblique plane of motion necessary to minimize the tendon forces to achieve a given activity.

Evolutionary significance

Tang [42] analyzed the skeletal specimens of a variety of vertebral animals, ranging from prehistoric and extinct animals to modern primates. The author highlighted five distinct evolutionary changes: first, the single-bone intercalated segment became multiple bony structures between the forearm and the metacarpus; second, a lengthy and a prominent equivalent of the pisiform, which was a dominant feature of the ulnar side of the carpus in animals requiring palmar flexion or weight bearing, evolved to the smallest carpal bone, much less prominent in comparison to those of ancient and giant animals; third, the ratio of the metacarpus to carpus; fourth, the changing roles of the carpal bones from alignment to stability and then to mobility and fifth, the presence of a broad distal part of the radius that causes the overlying tendons to protrude outwards and increases the distance from the tendons to their centers of motion, thereby creating greater moments to maintain or generate the dominant wrist motion pattern which is from radial extension to ulnar flexion, that is DT motion. Evolutionary significance has been ascribed to the DT plane, as it appears that the motion path may be unique to Homo Sapiens, and adaptations in carpal bone development may have abetted tool making, hunting and defensive abilities of early pro-hominids.[43]

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