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Influence of phase and dominance on ground reaction forces and upper extremity muscle activity during the modified-Closed Kinetic Chain Upper Extremity Stability Test

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Abstract

Background The Closed Kinetic Chain Upper Extremity Stability Test (CKCUEST) is a physical performance test designed to assess the upper extremity (UE) stability. However, only one outcome measure is provided for both UEs, limiting its application if the UEs are not similarly involved. Moreover, the changes in loads sustained by the support UE throughout the movement may influence the support UE stability. Additional knowledge on the underpinning biomechanical mechanics of the performance is therefore needed to better understand how to use the measure of the CKCUEST to design the athlete's physical ability development or recovery. This study aimed to investigate the influence of phase and dominance on kinetic and support UE muscular demand during a modified-CKCUEST touch.

Methods Twenty-five male multisport athletes (age: 26.0 ± 11.3 years; mass: 77.8 ± 23.3 kg; height: 179.0 ± 6.5 cm) performed the modified-CKCUEST, i.e. hands at half span apart. The ground reaction forces (GRF) and activity of eight perihumeral and scapulothoracic muscles of support UE were recorded and analyzed according to the UE dominance and phase (takeoff vs. landing). Statistical non-Parametric Mapping analyses were used to assess the effects of dominance and phase on the support UE GRF and the effects of dominance, phase, and muscle on the support UE muscle activity.

Results The scapulothoracic and perihumeral muscles of the support UE were activated at low-to-very-high levels during the modified-CKCUEST touch. Variations in muscular activity over a touch were required to sustain variations in loads in medial, vertical, and posterior directions. Lower loads were observed during the takeoff phase than those during the landing phase ($p < 0.05$). Despite similar muscular activities in both UEs, the dominant UE sustained higher medial loads than the non-dominant UE ($p < 0.05$), while opposite results were observed for posterior loads ($p < 0.05$).

Conclusions The modified-CKCUEST involves similar muscle activity of the support UE in response to varying loads sustained in different directions according to dominance. The quantitative assessment provided by the modified-CKCUEST score may be complemented by a qualitative observation of body displacements, allowing coaches and clinicians to identify limitations in the stability of the UEs.

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Keywords Shoulder, Physical performance test, Electromyography, Kinetic, Statistical Parametric Mapping

Background

The Closed Kinetic Chain Upper Extremity Stability Test (CKCUEST) is a physical performance test that was designed to assess the upper extremity (UE) stability during a closed kinetic chain task [1]. The CKCUEST is currently considered a sport-specific test performed to assess shoulder injury risk or return-to-sport after shoulder injury [2] in athletes who participate in sports requiring play above or below shoulder height, with or without throwing and with or without contact or collision [3]. Regardless of the unilateral or bilateral nature of the UE involvement in a sports activity or that of the shoulder injury, the CKCUEST provides a single outcome measure for both UEs [1]. Since shoulder functions and strength often differ depending on the side of athletes [4], symmetry in CKCUEST performance should be evaluated. Such additional knowledge on the biomechanical strategies of each UE during CKCUEST performance may help better design an athlete's physical ability development or recovery.

Through a two-handed push-up position on the ground, the CKCUEST aims to achieve a maximal number of touches alternatively using both hands during each series of 15 s. More precisely, one touch involves taking one hand off the ground (the takeoff phase), then touching the ground with the moving hand by crossing the support hand (the crossing phase), and replacing the moving hand onto the ground (the landing phase). Removing one support requires a significant amount of UE stability, particularly in the shoulder, to counteract the vertical load applied to the support hand. Indeed, the vertical load increases from 30 to 70% of body weight (BW) during the takeoff phase [5], with maximal values reached near after the crossing time [5], and then decreases to 30% during the landing phase. Similar vertical loads are reported for both the dominant and non-dominant UEs [5, 6]. Moreover, no changes are reported when the hand spacing varies from the inter-acromial distance to 150% of this distance [5]. Due to the lateral displacements occurring during a CKCUEST touch, the stability of the support UE is also challenged to sustain loads in the mediolateral direction, which are equivalent to about 20% of BW on average, with peak values of nearly 30% of BW [6]. In this direction, the non-dominant UE presents higher loads than the dominant UE when considering the maximal forces, while no bilateral differences remain when considering the average forces [6]. Such discrepancies in bilateral comparisons then demand a more detailed analysis of the variations in mediolateral loads during the CKCUEST touch to obtain deeper insights into the frontal plane forces experienced by the UE. In addition, the phases between the two-handed and one-handed push-up positions, and vice versa, may generate a BW redistribution between the support hand and feet. Since changing push-up positions in the sagittal plane influences the loads sustained by the support UEs [7], examining the anteroposterior loads can help determine whether the CKCUEST is required to manage support UE stability in this plane. Consequently, investigating the variations in loads sustained by the support UE in the vertical, mediolateral, and anteroposterior directions according to the phase of the CKCUEST touch may help to better understand how the stability of the support UE is challenged during the CKCUEST.

During a CKCUEST touch, the athlete alternates between bilateral and unilateral push-up poses while keeping straight UE. The stabilization of the UE and shoulder complex is mainly related to the serratus anterior and superior and lower trapezius muscular activities [8, 9] to limit the scapular motions in upward or downward rotation and anterior or posterior tilt as observed throughout a CKCUEST touch [5]. The middle trapezius activity [10] may contribute to limiting the winging of the scapular medial border [5] during the takeoff phase and rotating the scapula externally [5] during the landing phase. The posterior deltoid activity [10] may help to manage the anteroposterior forces sustained by the support UE when alternating between bilateral and unilateral push-up poses. On average, reduced scapular and humeral motions require moderate to high activity of UE muscles, especially for scapulothoracic and perihumeral muscles [10]. Consequently, monitoring the activity of scapulothoracic and perihumeral muscles throughout the CKCUEST touch may provide a more comprehensive understanding of their involvement in terms of activity level and timing in the CKCUEST performance.

The original procedure of the CKCUEST fixes the hand spacing at 36 inches (or 91.4 cm) [1], irrespective of the participant's anthropometry or shoulder health. This standardized hand spacing requires body position adaptations, such as placing the knees on the floor, for female participants [5] or participants with impingement syndrome [11]. For such adaptation that limit inter-individual comparisons, modified procedures were proposed, i.e., the modified-CKCUEST (m-CKCUEST). Specifically, adjusting the hand spacing to half the arm span [12] appeared to be the preferred hand spacing for the modified test to eliminate the influence of anthropometry on inter-individual comparisons [13]. However, changes in hand spacing may alter scapular and humeral positioning [5, 14], the loads experienced by the support UE, and the muscular demand to stabilize it, as previously observed in push-up exercises requiring different hand positioning [7, 15]. Thus, any change in an established test requires a validity reassessment. While the reliability of the m-CKCUEST outcome measure has been demonstrated [12, 16], the content-related validity still needs to be evaluated.

Therefore, the aim of this study was twofold: (1) to characterize the loads sustained by the support UE and its muscular activity throughout a m-CKCUEST touch, and (2) to assess the influence of phase and dominance on the kinetic and muscular demands of the support UE during a m-CKCUEST touch. This study hypothesizes that the m-CKCUEST touch would require variations between moderate and high levels in scapulothoracic and perihumeral muscular activities of the support UE in response to variations in loads in vertical, mediolateral, and anteroposterior directions. Additionally, it hypothesizes that the magnitudes of loads sustained, and the muscle activity levels of the support UE would be similar for both the takeoff and landing phases and for both the dominant and non-dominant UEs.

Materials and methods

Experimental design

This is an observational study performed in a laboratory setting (Fig. 1).

Participants

Twenty-five male athletes (age: 26.0 ± 11.3 years; body mass: 77.8 ± 23.3 kg; body height: 179.0 ± 6.5 cm; body mass index: 22.9 ± 2.13; weekly training: 4.5 ± 2.3 h; dominance, defined as the preferred throwing hand: 22 right-handed and 3 left-handed; sports: non-impact (n = 2), high impact (n = 2), overhead with hitting movements (n = 9), and overhead with hitting movements and sudden stops (n = 12) [17]), volunteered to participate in this study, which was approved by the local ethical committee (#2022-10-13-002). Every participant signed an informed consent according to the Declaration of Helsinki. The inclusion criteria were that the participants should be aged between 18 and 35 years and participating in a sports activity involving the upper limbs. The exclusion criteria were having undergone shoulder or upper limb surgery or having declared any upper limb or shoulder injuries over the six months preceding the data collection.

Data collection and procedure

First, the upper limb length, i.e., the distance from the C7 spinous process to the most distal point of the middle finger when the arms are abducted at 90° in the frontal plane with the thumb upward, was measured bilaterally using a measuring tape (dominant side: 91.0 ± 3.9 cm; non-dominant side: 91.1 ± 3.8 cm). Then, the participant performed a standardized warm-up consisting of 10 repetitions of elbow flexion-extension, humeral flexion-extension, push-pull, waist revolutions, and head revolutions using a two-kg medicine ball. This was followed by five wall push-ups with wide and narrow base hand placements, as well as 15 s of right-lateral-core, 30 s of frontal-core, and 15 s of left-lateral-core exercise [12].

After having shaved and cleaned the skin with alcohol, eight surface electromyography (EMG) electrodes (2000 Hz, Trigno Avanti Sensor, Delsys, Boston, United States) were placed bilaterally. Electrodes were located onto the upper trapezius (UT), middle trapezius (MT), lower trapezius (LT), posterior deltoid (PD), middle deltoid (MD), anterior deltoid (AD), and triceps brachii (TB) according to the SENIAM recommendations [18], and onto the serratus anterior (SA), namely on the seventh rib in the anterior axillary line [19]. Thereafter, eight positions for maximal voluntary isometric contraction (MVIC) were defined based on Dal Maso et al. [20], Schwartz et al. [21] and Rodriguez-Ridao et al. [22] (Table 1). Two 5-s MVICs (2-s progressive and 3-s of maximal effort) were recorded bilaterally for each muscle under verbal encouragement. A 30-s resting period and a one-min resting period were maintained between contractions and positions, respectively. Subsequently, four reflective markers were stuck on the distal and proximal parts of the second and fifth metacarpals of each hand.

According to the m-CKCUEST procedure described by Degot et al. [12], the participant started in a push-up position with middle fingers placed on two tapes stuck on two different force plates (2000 Hz, Kistler, Switzerland). Tapes were spaced at one half arm span, i.e., mean upper limb length (91.0 ± 3.8 cm). The task consisted of touching the ground outside the support hand, returning to the initial push-up position, and repeating alternatively with the other hand as fast as possible for 15-s. After a familiarization set, the participants performed three sets of maximal effort under verbal encouragement, interspersed by a 45-s recovery period. The participants did not receive any instructions on whether to start the test with the dominant or non-dominant upper extremity.

Fig. 1 Flowchart of the experimental procedure. MVIC for Maximal Voluntary Isometric Contraction; m-CKCUEST for Modified-Closed Kinetic Chain Upper Extremity Test

Table 1 Description of the MVIC tests

Targeted Muscle	Participant position	Handled dynamometer position	Exertion
Serratus anterior [21]	Prone, arm flexed at 90° with forearm extended	Hand	Scapular protraction
Upper trapezius [21]	Seated, arm along the side	Acromion	Scapular elevation
Middle trapezius [20]	Prone, arm horizontally abducted at 90°, thumb pointing up	Wrist	Horizontal arm adduction
Lower trapezius [20]	Arm horizontally flexed at 90° in line with the lower trapezius muscle fibers, thumb pointing upward.	Wrist	Horizontal arm flexion.
Anterior deltoid [21]	Seated, arm flexed at 90°	Wrist	Horizontal adduction
Middle deltoid [21]	Seated, arm abducted at 90°	Wrist	Arm abduction
Posterior deltoid [21]	Prone, arm along the body	Wrist	Arm extension
Triceps brachii[22]	Seated, elbow at 90° position, erect posture without back support	Wrist	Forearm extension

Three-dimensional trajectories of hand reflective markers were recorded with a 14 optoelectronic camera system (200 Hz, Qualisys, Gothenburg, Sweden). EMG, force plates, and kinematic signals were synchronized using QTM software (Qualisys Track Manager 2022.1) with an external trigger.

Data processing
Raw EMG signals were filtered (fourth-order band-pass Butterworth from 15 to 450 Hz), rectified, and smoothed (fourth-order low-pass Butterworth with a 15 Hz cutoff frequency). Signals were normalized by the mean maximal activation obtained across all MVIC positions over a 200-ms interval. Raw marker trajectories were filtered with a fourth-order low-pass Butterworth filter with a 10 Hz cut-off frequency and interpolated to 2000 Hz. Subsequently, the barycenter of each was computed regarding the four markers trajectories. Ground reaction force signals were filtered with a fourth-order low-pass Butterworth filter using a 20 Hz cut-off frequency [6] and normalized to BW. Ground reaction forces and barycenter of the hands were then expressed in a local reference system, defined as the position of the right hand at the start of the test. The x-axis pointed medially, the y-axis upwardly, and the z-axis toward the participant's feet. Only for the left-hand support and for the purpose of dominance comparison, mediolateral forces were multiplied by (-1) so that positive values corresponded to forces pointing medially. In accordance with the moving hand trajectory, medially oriented forces during the takeoff phase were defined as resistive loads, i.e., loads in the opposite direction of the moving hand trajectory, and as propulsive loads, i.e., loads in the direction of the moving hand trajectory, during the landing phase.

The touches performed during the second and third sets were averaged to compute the m-CKUEST score [12]. For EMG analysis, the second and third sets were considered, and the first four touches of each set were removed to account for the time needed to start the test. Subsequently, the penultimate or last touch of each set was kept to get the same number of touches per hand. Two phases were identified during a touch cycle. The takeoff phase started from the position where vertical GRF were equally distributed between the two hands to the crossing time, defined by the maximum absolute value of the moving hand barycenter on the x-axis. The landing phase started one frame after the hand-crossing time and lasted until the two vertical GRFs were again equally distributed on both hands. For statistical purposes, the touch duration was normalized to 100%, with the takeoff phase lasting from 1 to 50% and the landing phase from 51 to 100%. Based on all touches included in the analysis, EMG and GRF signals were averaged by phase and UE dominance.

Statistical analyses
Data are represented as mean ± standard deviation and range values (min; max). Muscle activity was defined as low (< 20%), moderate (20–40%), high (41–60%), or very high (> 60%) [23]. For the landing phase, signals were flipped to compare the equivalent parts of the movement. Subsequently, Statistical non-Parametric Mapping (SnPM) three-repeated-factors analysis of variance (SnPM{F}) was conducted to examine the effect of *dominance* (dominant vs. non-dominant UE), *phase* (takeoff vs. landing), and *muscle* (SA, UT, MT, LT, AD, MD, PD, and TB), as well as their interactions on the support UE muscular activity. Additionally, a three-repeated-factors analysis of variance (SnPM{F}) was conducted to determine the effects of *phase* (takeoff vs. landing) and *dominance* (dominant vs. non-dominant UE) and their interactions on GRF for each direction. When SnPM{F} revealed significant effects, post-hoc tests (SnPM{t}, paired t-tests) were performed with Bonferroni's correction. Only significant clusters corresponding to more than 5% of the touch duration were considered. To determine the magnitude of differences, Cohen's d effect sizes were computed and interpreted as small for d ≈ 0.20, medium for d ≈ 0.50, and large for d ≈ 0.80 [24]. SnPM analyses were performed using the open-source Factorial ANOVA and post-hoc tests for Statistical non-Parametric Mapping package [25] in MATLAB based on the sp1md package [26] for MATLAB. The level of significance was set at $p < 0.05$.

Results

The m-CKCUEST score was 27.0 ± 2.5 touches (takeoff phase: 0.27 ± 0.03s, 50.8 ± 2.5% of the total touch duration; landing phase: 0.26 ± 0.03s, 49.2 ± 2.5% of the total touch duration), and the muscular and kinetic analysis was based on 21.1 ± 2.8 touches (16;26) per participant.

Ground reaction forces during the m-CKCUEST touch

During a m-CKCUEST touch (Fig. 2), the GRF in the vertical, medial, and posterior directions increased during the first 10% of the takeoff phase. The GRF in the posterior direction remained similar until the last 10% of the landing phase, while the GRF in medial and vertical directions increased again from the last 50% of the takeoff phase until the first 10% of the landing phase. All the GRF decreased in the last 10% of the landing phase.

Effect of phase and dominance on the ground reaction force during the m-CKCUEST touch

SnPM{F} revealed no significant interaction of *phase*dominance* ($p > 0.05$), a significant effect of *phase* for GRF in all the directions, and a significant effect of *dominance* for GRF in the medial and posterior directions (see Figures S1 to S3 in the additional file). GRF were significantly lower during the takeoff phase than the landing phase for the medial (d = (min: 0.13;max: 1.63), small to large effects), vertical (d = (0.05;2.07), trivial to large effects) and posterior (d = (0.17;0.76), small to large effects) directions (Fig. 2). In the medial direction, the dominant UE presented significantly higher GRF than the non-dominant UE at mid-course (d = (0.24;0.30), small effects) in the takeoff and landing phases and hand crossing (d = (0.34;0.36), small effects) (Fig. 2). In the posterior direction, the dominant UE presented significantly lower GRF than the nondominant UE at the beginning of the takeoff phase (d = (0.44;0.47), medium effects), and at hand crossing (d = (0.43;0.51), medium effects) (Fig. 2). All the post-hoc pairwise comparisons are presented in Table S1 and Table S2 of the additional file.

Muscle activity during m-CKCUEST touch

Regarding scapulothoracic muscle involvement (Fig. 3), the SA activity of the support UE was moderate between the hand takeoff phase and the beginning of the landing phase, which subsequently increased to be very high at the mid-landing phase and decreased to be moderate again at the hand landing phase. The UT activity was moderate at the hand takeoff and remained low throughout the touch, while MT and LT muscles presented low activities throughout the touch, which was excepted at the time of hand crossing, during which both these muscles were highly activated. For perihumeral muscles,

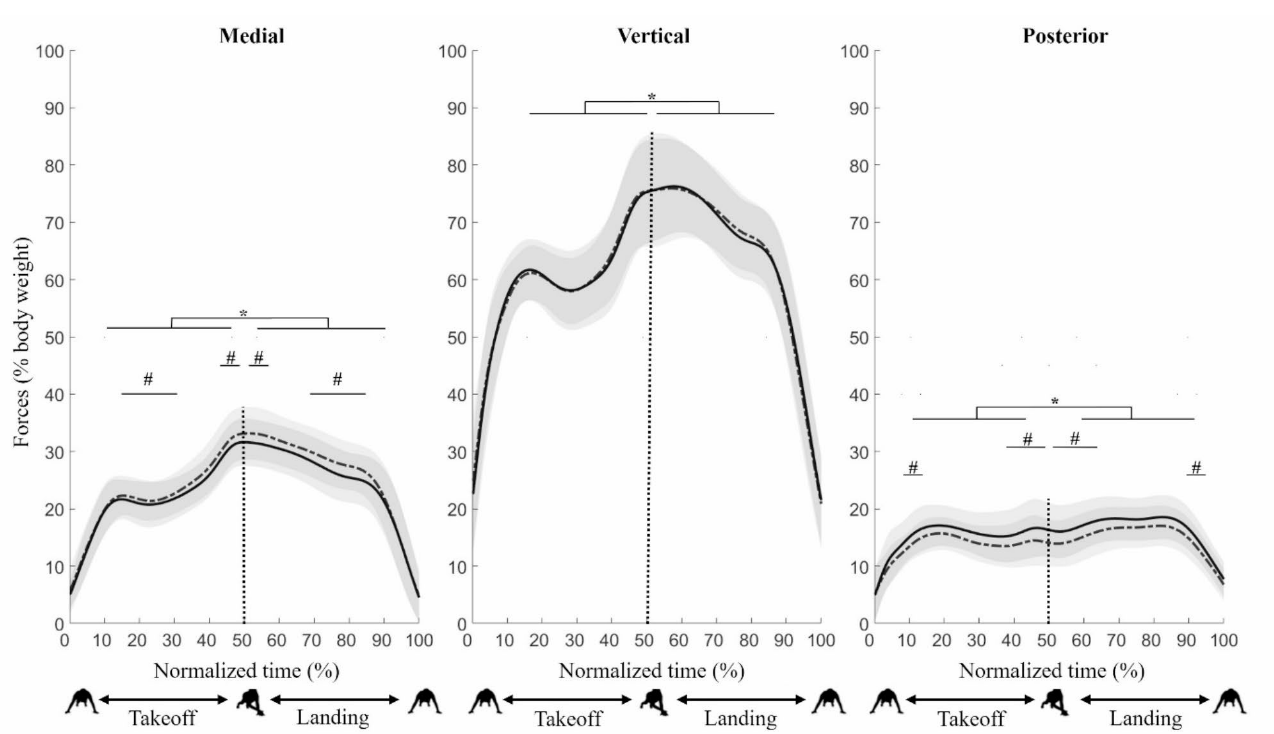

Fig. 2 Mean (± standard deviation) ground reaction forces for the medial (left), vertical (middle) and posterior (right) directions according to the normalized modified-Closed Kinetic Chain Upper Extremity Test touch duration for the dominant (--) and nondominant (–) support upper extremities. ··· highlight the crossing hands time. * depicts significant differences ($p < 0.05$) between the takeoff and landing phases; # depicts significant differences ($p < 0.05$) between the dominant and nondominant upper extremities

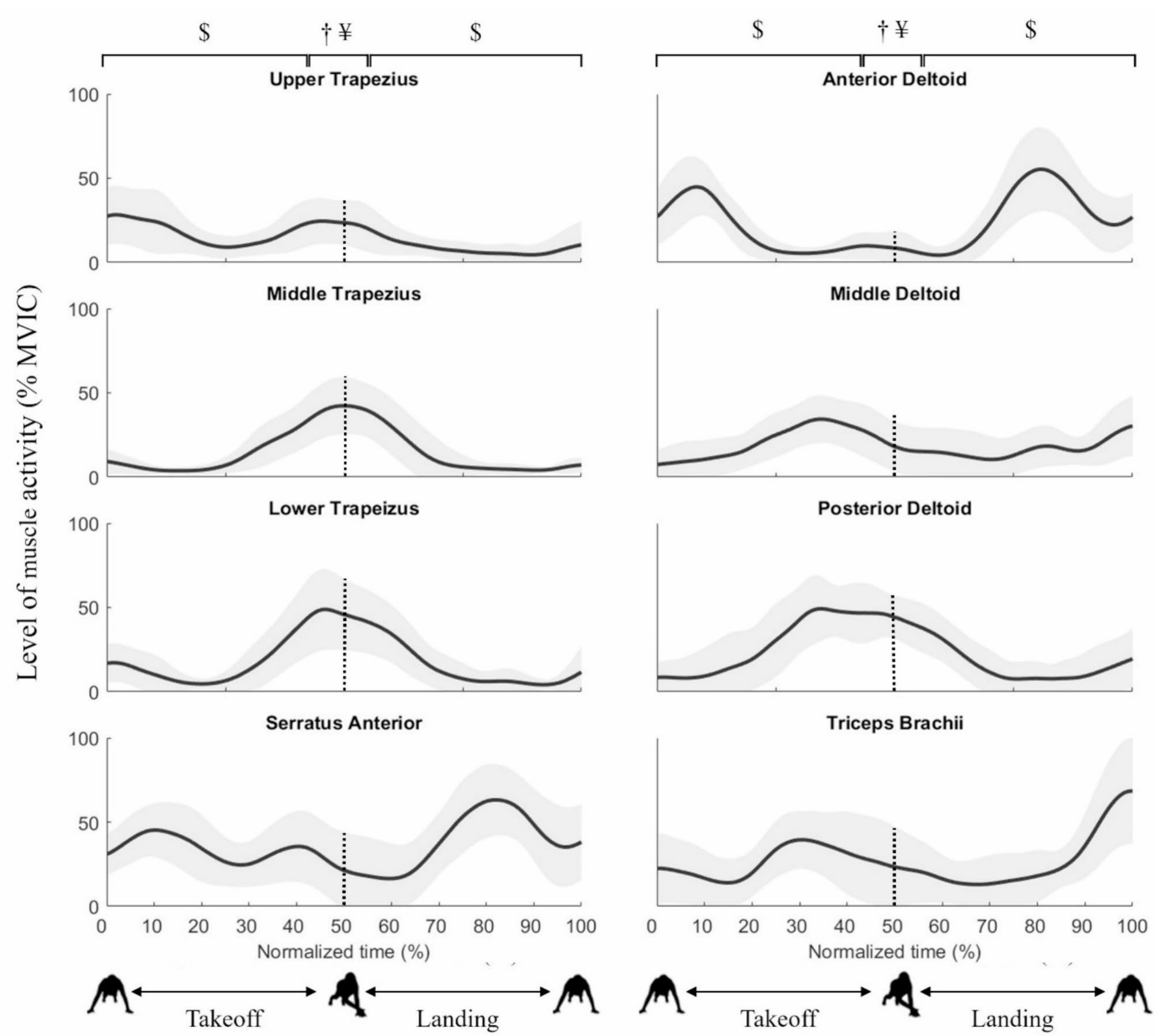

Fig. 3 Mean (± standard deviation) support upper extremity muscle activity according to normalized for modified-Closed Kinetic Chain Upper Extremity Test touch duration, with MVIC for Maximum Voluntary Isometric Contraction. ··· highlight the crossing hands time. $ depicts significant effect of interaction *muscle*phase* ($p < 0.05$); † depicts significant main effect of *muscle* ($p < 0.05$); ¥ depicts significant main effect of *phase* ($p < 0.05$). Pairwise comparisons are presented in the Table S3 of additional file 1

AD was activated moderately at the hand takeoff, while the MD and PD were lowly activated; subsequently, AD activity decreased to become low, whereas the MD and PD activities increased to moderate and high levels, respectively, during the second half of the takeoff phase. At the beginning of the landing phase, MD and PD activities decreased to low levels until the hand landing, while AD activity increased to a high level at the mid-landing phase and decreased to a moderate level at the hand landing. Throughout the touch, TB activity varied from low to moderate levels and increased to a very high level at the hand landing.

Effect of muscle, phase and dominance on the muscle activity during the m-CKCUEST touch

SnPM{F} revealed no significant effects of interaction *muscle*phase*dominance* ($p > 0.05$), *dominance*phase* ($p > 0.05$), and *muscle**dominance ($p > 0.05$), but a significant effect of *muscle*phase* from 1 to 45% and from 56 to 100% of the m-CKCUEST touch and significant main effects of *muscle* and *phase* from 45 to 56% of the touch (see Figure S4 in additional file 1). Since SnPM{F} reported no significant effect of *dominance*, the muscular activities of the UE were averaged in each muscle for subsequent analyses. All the post-hoc pairwise comparisons are presented in Table S3, and effect size values are presented in Tables S3and S4 of the additional file 1.

From 1 to 20% of the touch, i.e., the first third of the takeoff phase, SA and AD were significantly more activated than all other muscles and the UT activity was significantly higher than those of MT and LT. From 20 to 45% of the touch, i.e., the last two-thirds of the takeoff phase, PD and MD were significantly more activated than AD and SA and TB were similarly activated. From 45 to 55% of the touch, i.e., the crossing time, all the muscles were significantly more activated in the last 5% of the takeoff phase than the first 5% of the landing phase (d = (0.00;0.36), trivial to small effects), and PD, LT, and MT were significantly more activated than all the other muscles. From 55 to 65% of the touch, i.e., at the beginning of the landing phase, UT was significantly less activated than MT and LT and PD was significantly more activated than AD, MD, and TB. From 65 to 80% of the touch, AD and SA activities were significantly higher than those of the other muscles, and from 80% to the end of the touch, SA and TB muscles were significantly more activated than all the others. When the muscle activities were compared between both the phases, UT, PD, and MD were found to be more activated during the takeoff phase than the landing phase, while SA, AD and TB were more activated during the landing phase than the takeoff phase (Fig. 3).

Discussion

The aim of this study was to characterize the loads sustained by the support UE and its muscular activity throughout a m-CKCUEST touch and to assess the influence of phase and dominance on these loads and muscle activities. The main findings of this study showed that (i) sustaining loads exerted in vertical, medial, and posterior directions required low to very high activities of the support UE scapulothoracic and perihumeral muscles during a m-CKCUEST touch; (ii) regardless of the direction, the sustained loads of the landing phase were higher than those of the takeoff phase; and (iii) despite similar muscular activities for both UEs, the dominant UE sustained higher medial loads than the non-dominant UE, while opposite results were observed for posterior loads.

Since the CKCUEST is easy to use in sports and clinical settings, its integration in batteries of physical performance tests is recommended for assessing athletic performance, injury prevention, or return-to-sport [2, 3, 16, 27]. Since the standardized hand spacing of the original testing procedure [1] demands adaptations for some populations [5, 11], modified procedures have been proposed, especially procedures with variations in hand spacing [5, 12, 13]. In this context, the m-CKCUEST [12], normalizing hand spacing to participants' body dimensions, is feasible for various healthy athletes [28], athletes after shoulder injury [29] or patient-athlete populations [30] with no required procedure adaptation. During the m-CKCUEST touch, the support UE resisted the gravity and the lateral movements, as previously reported for the original CKCUEST [5, 6]; however, it may also resist the sagittal disturbances [7]. Nonetheless, using a time-series analysis, our study highlighted that the support UE had a resisting role during the takeoff phase, and played also a propelling role during the landing phase, with a propelling contribution higher than resisting one. The bilateral nature of the m-CKCUEST may indicate that the sustained loads by the support UE would be similar for both sides. Our findings confirmed such assertions for the vertical direction, as previously observed for the original CKCUEST [5, 6]; however, dominance influenced the loads in frontal and sagittal planes. Welch et al. [6] reported higher maximal values of frontal plane loads for the non-dominant UE, while this study found higher loads for the dominant side. Such discrepancies may be due to the differences in hand spacing, i.e., fixed distance for Welch et al. [6] vs. body normalized hand distance for our study, and in the outcome loads measure, i.e., maximal values for Welch et al. [6] vs. force curves for this study. When considering the forces on the anteroposterior axis, the non-dominant UE sustained more posterior loads than the dominant UE. Being on the non-dominant UE would generate disturbances, leading to the involvement of non-dominant UE in the m-CKCUEST performance being less efficient compared to the dominant UE, which could be explained by deficit in strength and motor control in the non-dominant UE than in the dominant UE [31]. Consequently, our findings revealed that the m-CKCUEST assesses the resisting and propelling abilities of the support UE and suggested that biomechanical strategies of the dominant UE might be more effective than those of non-dominant side, due to lower anteroposterior disturbances.

The CKCUEST performance is achieved through a high mediolateral velocity of the moving hand [6], associated with a stable base provided by the support UE. A previous study reported moderate-to-high muscular activity on average [10] during the CKCUEST. When applying time-series analysis, the muscular activities varied from low to very high levels, highlighting that the stabilization of the support UE may demand coordinated involvements of the scapulothoracic and perihumeral muscles during the m-CKCUEST touch. At the moving hand takeoff, anterior deltoid activity increases, generating arm flexion torque that is responsible for the concomitant increase in the ground reaction force oriented toward the feet. This activity was coordinated with those of the upper trapezius and serratus anterior, which may fix the shoulder elevation and scapular upward rotation [32], to ensure proper glenohumeral joint positioning.

When the BW was distributed on three supports, i.e., the support hand and both the feet, the arm flexion torque was counterbalanced by increased activity of posterior and middle deltoids associated with that of triceps brachii [33]. Together, the arm extensors and abductors may also prevent the trunk rotation relative to the support UE, i.e., horizontal adduction of the support arm, which can occur during the takeoff phase. At the end of the takeoff phase, the middle and lower trapezius may be activated to fix the medial border and inferior angle of the scapula onto the thoracic wall, offering potentially a stable base to initiate the propelling action following hands crossing. Along the landing phase, the previous arm extensor action may be compensated by the arm flexor action produced by the high anterior deltoid activity in association with the serratus anterior. Throughout the m-CKCUEST touch, the serratus anterior and the triceps brachii played their primary function, which is to maintain the scapula against the posterior thoracic cage [8] and to extend the elbow [33], respectively. Notably, the triceps brachii activity of the support limb increases at the end of the landing phase, probably for initiating the propulsion of the following touch. In addition, although the muscular activities were similar when the dominant and non-dominant UEs were on the support side, the support UE muscles of the dominant limb may be mainly involved in resisting and propelling during the takeoff and landing phases, respectively, while the non-dominant UE muscles may also need to manage the disturbances in sagittal plane during the touch. Consequently, based on time-series analysis, our study pointed out that a m-CKCUEST touch is achieved through variable muscular activity levels at the support UE, and required coordinated involvement of the scapulothoracic and perihumeral muscles.

Despite the several insights of this study, it has limitations that warrant discussion. First, only the activity of the UE superficial muscles was recorded, although deep muscles as rotator cuff muscles play the primary role in glenohumeral joint stability [34]. Further studies using intramuscular EMG should be conducted to address this issue to investigate the role of the rotator cuff muscles in managing the stability of the glenohumeral joint during the m-CKCUEST. Second, our results are only applicable to the m-CKCUEST procedure, and the inclusion of only healthy multisport male athletes limits the generalization of these findings to other populations, such as women. Further studies should include a population with different characteristics to determine whether specific strategies to achieve m-CKCUEST are used according to age, sex, unilateral sports practice, or shoulder problems.

This study has several implications for coaches and clinicians when assessing athletes' UE based on m-CKCUEST. The m-CKCUEST score can only provide general information on the physical condition of the UEs together, as the biomechanical strategies differ between the dominant and non-dominant sides. Consequently, only a qualitative analysis through participant observations may help detect the strengths and weaknesses of each UE. Since the perihumeral muscles are mainly activated at the beginning and end of the m-CKCUEST touch, the trunk displacements in the anteroposterior direction may reveal a weakness in the perihumeral muscles. Specifically, if the support UE shoulder moves ahead of the support hand fingers at the moving hand takeoff and during the landing phase, it may indicate a weakness in the arm flexors. Conversely, if the support UE shoulder moves ahead of the support hand palm during the takeoff phase, it may suggest a weakness in the arm extensors. Since the serratus anterior muscle is activated throughout the m-CKCUEST touch, a trunk sagging may point to a weakness in the serratus anterior muscle. As the trapezius muscles are mainly activated at the hand crossing, a scapular medial border and/or inferior angle winging at this phase may reveal a weakness in the middle and/or lower trapezius muscle, respectively. Considering that the touches can be performed rapidly, such parasitic motions can be difficult to observe in real time. The development of a markerless video analysis system using a smartphone camera could serve as an interesting tool to better qualitatively analyze the involvement of each UE in the m-CKCUEST performance.

Conclusions

In conclusion, by conducting time-series analyses, this study reveals that the achievement of a m-CKCUEST touch demands both the production of resisting and propelling loads to perform the touch, but also to ensure support UE stability by managing the changes in vertical and posterior loads sustained throughout the touch. These changes in loads demand coordinated involvement of the scapulothoracic and perihumeral muscles of the support upper extremity to perform the touch and managing stability of the support UE. Performing the m-CKCUEST involves similar muscular recruitment for both the UEs; however, the dominant UE muscles mainly counteract the disturbances in the mediolateral direction, while the non-dominant UE muscles may also counteract the disturbances in the anteroposterior direction. This suggests that, with no additional measuring tools, coaches and clinicians may observe the abnormal displacement of the body and scapula to identify limitations in UE stability.

Abbreviations

CKCUEST	Closed Kinetic Chain Upper Extremity Test
m-CKCUEST	modified-Closed Kinetic Chain Upper Extremity Test
UE	Upper extremity
GRF	Ground reactions forces
BW	Body weight
SA	Serratus anterior
UT	Upper trapezius

MT	Middle trapezius
LT	Lower trapezius
PD	Posterior deltoid
MD	Middle deltoid
AD	Anterior deltoid
TB	Triceps brachii. MVIC: Maximal voluntary isometrical contraction
EMG	Electromyography
SnPM	Statistical non-parametric mapping

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-024-01043-9.

Supplementary Material 1

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Author contributions
TDS performed the data collection, data analysis and wrote the manuscript. MD contributed to the study design and performed the data collection. YB participated in the study design and data analysis and contributed to manuscript writing. IR contributed to the data analysis, study design and manuscript writing. All authors read and approved the final manuscript.

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Data availability
The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This research was approved by the ethical committee (Research ethics committee of the comue Lyon university #2022-10-13-002). Participants were informed of the experimental procedure and provided their written informed consent prior to first testing session.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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