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Muscle activity in throwing with the dominant and non-dominant arm

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Muscle activity in throwing with the dominant and non-dominant arm

Muscle activation patterns of the dominant and non-dominant arm were compared during two unconstrained throwing tasks (dart throws, underhand throws). Electromyographic (EMG) signals were recorded from shoulder (anterior and posterior deltoid), upper arm (biceps and triceps brachii) and hand (thenar) muscles in 12 healthy volunteers. Mean and peak EMG amplitudes of both arms did not differ significantly and their EMG curves were nearly congruent. Also the timing of the EMG bursts was alike for the dominant and non-dominant arm in both throwing tasks, with the exception of one muscle (posterior deltoid). EMG activity of this muscle, which is an antagonist during dart and underhand throws, started significantly later on the non-dominant side than on the dominant side. The mean interlimb differences were 17 ms for dart throws and 35 ms for underhand throws. Higher spatial accuracy of throws was associated with less hand (thenar) muscle activity regardless of the side (dominant, non-dominant). The conspicuous similarity of the EMG curves of both arms speaks in favour of motor equivalence, indicating that the activation of dominant and non-dominant agonist muscles is controlled by the same motor program during unconstrained throwing.

Keywords: electromyogram; motor equivalence; throwing; bilateral symmetry; dominant and non-dominant arms
Introduction

The concept of motor equivalence in human motor control has been proposed by prominent researchers for about 100 years (Bernstein, 1967; Head, 1920; Lashley, 1933; Schmidt, 1975; Sherwood, 2014). It refers to the fact that one can perform the same movement with different limbs and different muscle groups. A classic example is cursive handwriting, where letter shapes reflecting individual style are preserved, whether the letters are written small on paper or large on the blackboard by each hand, or written in the sand with the foot (Wing, 2000). Another example is the ability of trained sportsmen to dribble and shoot skilfully with either hand or foot (Sherwood, 2014). Motor equivalence implies that an engram (Bernstein, 1967) or generalized motor program (Schmidt, 1975) specifies invariant characteristics of the movement, such as the relative timing of the movement phases and the direction changes, the sequence of events, and the relative forces of agonist/antagonist muscle contractions. Key features of movement that remain more or less constant regardless of effector are specified by the highest level of a hierarchical motor control system, while variations of metrical characteristics (e.g. magnitude, velocity, force) are set by a lower level of the system according to Bernstein (1967). Because of such variations, motor equivalence does not necessarily require that movement accuracy is invariable and effector-independent.

Handedness refers above all to fine motor skills such as writing and the use of tools, but the dominant limb is also usually preferred when throwing (McManus, Porac, Bryden, & Boucher, 1999). About 90 percent of adults prefer the right arm for unimanual throwing actions (Loffing, Solter, & Hagemann, 2014). Muscles used in throwing exhibit precise timing of reciprocal and sequential contractions to accomplish...
Evidence for motor equivalence of both upper limbs in unconstrained throwing tasks has remained inconclusive up till now (Sherwood, 2014). Concerning the symmetry of muscle activation patterns during unconstrained unimanual throwing tasks, two previous studies compared electromyographic (EMG) signals of dominant and non-dominant arm muscles and arrived at conflicting results. Waterhouse (2014) evaluated four young volunteers over a course of five days of dart throwing and found that the non-dominant limb was significantly less accurate than the dominant limb. Yet co-contraction between agonist and antagonist muscles (biceps and triceps brachii) was not notably different between dominant and non-dominant limbs, and did not change substantially with practice. The similarity in the EMG data led to the conclusion that throwing is controlled by the same motor program regardless of which limb performs the movement (Waterhouse, 2014). On the other hand, Morrison and Anson (1999) found a delayed onset of antagonist (brachioradialis) muscle activity in dart throws performed with the non-dominant hand. As for the lower limbs, previous EMG studies reported differences between dominant and non-dominant leg muscle activations during walking (Ounpuu & Winter, 1989; Pierotti, Brand, Gabel, Pedersen, & Clarke, 1991) and standing (Mondal, Changte, Gayen, & Chatterjee, 2014). Moreover, kinematic and kinetic analyses of overarm throws made by dominant and non-dominant arms found significant asymmetries (Hore, O'Brien, & Watts, 2005; Hore, Watts, Tweed, & Miller, 1996).
The present study of normal inexperienced volunteers compares the EMG activity of shoulder, upper arm, and hand muscles during throws made by the right and left arms with two different movement techniques (dart throw, underhand throw). Untrained volunteers were examined to rule out effects of previous practice. Intensive training is known to change the EMG pattern of the preferred arm during aimed throwing, as it has been demonstrated for expert dart throwers (Obayashi, Tamei, Imai, & Shibata, 2009) and for advanced handball (Rousanoglou, Noutsos, Bayios, & Boudolos, 2014) and basketball players (Pakosz, 2013). Training may accentuate differences between the dominant and non-dominant arm. Well-trained handball players show higher peak velocities and increased ranges of their major joint movements when throwing with their dominant arm, compared to the non-preferred side (van den Tillaar & Ettema, 2009). The throwing (dominant) arm of trained baseball players has an increased glenohumeral stiffness that is associated with enhanced EMG activity of the M. serratus anterior during a stiffness test, as compared to the non-dominant arm (Thomas et al., 2013).

Effects of intensive training on muscle activation patterns and kinematics of the preferred arm are therefore known. However, it is still open as to whether untrained persons show comparable muscle activation patterns between their dominant and non-dominant limbs during throwing. If there are significant differences between these EMG patterns, this would not support the notion that throwing movements of both arms are steered by a common superordinate motor program.
Materials and Methods

Participants and task

Twelve healthy volunteers (6 women) participated in the experiments (age 24.9 ± 5.0 years, body height 175 ± 11 cm, weight 73 ± 19 kg; mean ± standard deviation SD). They had at most minimal experience with dart throwing; none of them played darts or practiced any other throwing sports on a regular basis. Eleven participants were right-handed according to a questionnaire (Annett, 1970), and consistently used the right hand to throw. One participant was left-handed. Exclusion criteria were any motor disorders affecting arm and hand movements, posture, and gait. All volunteers gave informed written consent for participation and publication. The research was conducted with the formal approval of the local ethical committee of the Medical Faculty of Christian-Albrechts-University (Kiel, Germany).

Participants threw steel tip darts (weight 22 g) at a target drawn on paper attached to a vertical softwood plate at a distance of 2.37 m. The target consisted of six concentric circles, the radii of which increased in increments of 5 cm from 2.5 cm (bulls eye) to 7.5 cm, etc. to 27.5 cm (outermost circle). To describe throwing accuracy with a score, target zones between circles were numbered 7 (bulls eye), 6, 5, etc.; zone 1 was outside the outermost circle. The standing participants used two different throwing techniques (see supplementary figure 1) with each hand: A) The dart throw, involving vigorous elbow joint extension and some shoulder joint flexion (Lohse, Sherwood, & Healy, 2010; Nakagawa et al., 2013). Here the target centre was at eye level (166 ± 11 cm). B) An underhand throw involving a sweeping forward flexion of the shoulder joint. Here the height of the target centre was at two-thirds the height of eye level (111 ± 7 cm). Participants were not allowed to step over the starting line while throwing, but
their movements were not otherwise constrained. Without prior practice, each participant threw four series of 30 numbered darts each (4 x 30 trials). These four series corresponded to the conditions: (D_DOM) dart throw with dominant hand, (D_NDOM) dart throw with non-dominant hand, (U_DOM) underhand throw with dominant hand, (U_NDOM) underhand throw with non-dominant hand. The 30 darts were thrown in quick succession during each series. Pauses separated the different series, the order of which was counterbalanced across participants.

Instrumentation

Pairs of disposable self-adhesive Ag-AgCl electrodes (Arbo® H124SG, Germany) with a pick-up diameter of 15 mm were attached to the skin of the arm and hand for non-invasive EMG recordings. The skin was treated with medical abrasive paste to reduce electrode-skin impedance before the electrodes were placed above five muscles according to published guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000): anterior deltoid (AD) and posterior deltoid (PD) muscles, electrodes about 4 cm anterior to acromion on line to thumb (AD), and about 4 cm posterior to acromion on line to little finger (PD); biceps brachii (BIC), electrodes between acromion and fossa cubiti on muscle belly; triceps brachii (TRI), electrodes on long head of the TRI, about 3 cm medial to a line connecting olecranon and acromion; and thenar muscles (THE): electrodes on thenar of the hand, oriented along the direction of the 1st metacarpal bone. Bipolar configurations with an inter-electrode distance of ~2.5 cm were used. For later normalization of the EMG amplitudes (see below), maximum voluntary contractions were performed. The deltoid muscles (AD, PD) were tested by forceful flexion/extension of the shoulder against fixed resistance, with the elbow extended. With the elbow joint bent at a right angle, TRI and BIC contracted maximally against
resistance. The muscles were tested by executing a pinch grip with maximum force. Maximum power grip force of either hand (average of 3 trials) was determined with a Baseline® Hydraulic Hand Dynamometer (Elmsford, NY, USA). An accelerometer (Noraxon Inline 3D-16G) was fastened with tape and Velcro straps to the dorsum of the wrist. The accelerometer’s x-axis pointed along the long axis of the forearm towards the 3rd metacarpal bone, the y-axis perpendicular to the x-axis towards the styloid process of the radius; the z-axis was oriented perpendicular to the xy-plane, pointing in the volar (palmar) direction. Acceleration was measured in g ($1g = 9.81 \text{ m/s}^2$).

EMG electrodes and the accelerometer were connected to an eight channel Myosystem 1400 L (Noraxon®, Scottsdale, AZ, USA) device with the following specifications: differential amplifier, input impedance >100 MOhm, common mode rejection ratio >100 dB at 60 Hz, sensitivity 1 μV, baseline noise <1 μV RMS, bandwidth 10 - 500 Hz. EMG and accelerometer signals were sampled at a rate of 2000 Hz per channel and A/D converted with a digital 12 bit resolution per channel. Data were recorded for 800 ms during each throw, temporally aligned to movement onset at 300 ms (i.e. 300 ms pre-trigger, 500 ms post-trigger sampling time). Movement onset was defined as the instant when acceleration of the wrist in x-direction exceeded 1.25 g during dart throws, or 2.25 g during underhand throws. Preliminary tests had shown that these trigger thresholds reliably indicate the start of the vigorous throwing movement. EMG and acceleration data were stored together with video images for later offline processing using Noraxon® software (Myo Research XP, Master Edition 1.07). EMG signals of each muscle were full-wave rectified, smoothed with a root mean square window of 20 ms, and amplitude-normalized to the highest activity level (mean amplitude for 50 ms) measured in the set of MVC contractions (see supplementary figure 2). Such normalization to MVC values (unit %MVC) is an established method.
that minimizes the influence of varying anatomical and physiological conditions (e.g. skin thickness and conductance, electrode impedance) to enable inter- and intraindividual comparisons (Burden, 2010).

Data from the 30 throwing trials per participant and condition were averaged to obtain mean individual EMG and acceleration curves (each lasting 800 ms). Average and peak amplitudes of these curves were determined. To compare both sides we subtracted the NDOM from the DOM signals to obtain the difference curves (DOM minus NDOM) for dart and for underhand throws. The individual curves were averaged to obtain grand averaged EMG profiles (group results) for each arm and throwing technique (i.e. conditions D.DOM, D.NDOM, U.DOM, U.NDOM). The difference curves were also averaged across participants, and the resultant mean differences (DOM–NDOM) and their 95% confidence intervals were plotted against time (see supplementary figure 3). Onset and offset of the discrete bursts of EMG activity were determined trial by trial, since averaging muscle activity curves blurs the timing pattern. Onset and offset were defined as activity exceeding / falling below the half-maximal height of the burst of each analysed trial (supplementary figure 2). The conventional threshold of activity exceeding mean baseline activity plus three standard deviations (Maslovat, Carlsen, Chua, & Franks, 2009; Tenan, Tweedell, & Haynes, 2017) was not applicable due to frequent pronounced EMG signals in the 300 ms pre-trigger time (i.e. no resting baseline), when the arm was cocked to throw.

**Data analysis**

For each participant and condition, we calculated average values of EMG amplitudes (mean and peak values) and timing (EMG burst onset and offset) for each muscle, and mean values of the peak wrist accelerations. Analyses of variance (ANOVA) for
repeated measurements with hand (DOM, NDOM) and throwing technique (dart, underhand) as within-subject factors were performed on the subject-wise means, using IBM SPSS statistics software (version 22). Interactions may show differences between DOM and NDOM that depend on the technique. Partial eta squared (\(\eta^2\)) are reported to indicate the size of experimental effects. Post-hoc paired sample t-tests were calculated to test for hand- and technique-specific differences. Throwing accuracy was described with the aforementioned target zone numbers (range: 1-7). To describe improvements of accuracy over the series of 30 throws using learning curves, the mean accuracy of each trial, averaged across participants, was calculated, and polynomials were fitted to the data of the series of trials (see Figure 1). Pearson’s correlation coefficients \(r\) were used to evaluate possible correlations between changes in throwing accuracy and concomitant changes in EMG/acceleration variables. These variables were the timing (burst onset, offset) and the amplitudes of the signals, which had been determined and averaged across participants trial by trial.

**Results**

The learning curves show improvements in throwing accuracy over the series of 30 trials for both techniques and for both arms (Figure 1). As expected, accuracy of the dominant arm was significantly better than accuracy of the non-dominant arm (ANOVA \(F_{1,11}=16.62, p=0.002, \eta^2=0.6\)). Moreover, dart throws were significantly more accurate than underhand throws (\(F_{1,11}=14.19, p=0.003, \eta^2=0.56\)), but there was no significant interaction between the factors technique and hand (\(F_{1,11}=0.099, p=0.76\)). The mean scores of accuracy are listed in Table 1.

Ensemble averaged EMG curves (group results) and accelerometer data of the dominant (DOM) and non-dominant (NDOM) arm are superimposed in Figure 2. The
curves of both sides are nearly congruent, and the corresponding mean and peak EMG amplitudes and accelerations showed no significant differences between DOM and NDOM in either throwing technique (Table 1). There was only a trend (p=0.056) towards less THE activity of the dominant hand (DOM<NDOM) in dart throws. The ensemble averaged difference curves (DOM–NDOM group results) generally run near the zero line (supplementary figure 3). Deviations from zero occur transiently in a few short periods, as evident from the 95% confidence intervals of the mean difference curves. In dart throws, THE and TRI activity of the non-preferred side were somewhat increased after movement onset, i.e. shortly after time 300 ms (NDOM>DOM for THE at ~320 ms, for TRI at ~380 ms). Deceleration of dart throws performed with the non-preferred hand appeared to be delayed, with a negative difference of accelerometer (x-direction) signals around 500 ms (DOM–NDOM < 0). In underhand throws, TRI activity of the dominant hand was transiently enhanced (DOM>NDOM) around time 430 ms (supplementary figure 3). We did not perform statistical post-hoc analyses of these temporary DOM–NDOM side differences, as this would have introduced a multiple testing bias. Onset and offset times of the EMG bursts are illustrated in Figure 3 and listed in Table 2. The timing of DOM and NDOM muscle activations was very similar, with a mean difference of less than 20 ms. Nevertheless, ANOVA revealed a significant interlimb difference in the PD onset time (F1,11=9.46, p=0.011, partial \( \eta^2=0.46 \)) regardless of the throwing technique (interaction not significant: F1,11=2.80, p=0.122). EMG bursts of this shoulder muscle, which is an antagonist during dart and underhand throws, started earlier on the dominant side than on the non-dominant. The average delay of NDOM PD onset was 17 ± 27 ms (mean ± SD) for the dart throw and 35 ± 42 ms for the underhand throw (Figure 3, Table 2).

Unsurprisingly, data from the two throwing techniques differed significantly
(Tables 1 and 2). Underhand throws involved higher mean EMG activity of BIC (F1,11=14.73, p=0.003, partial $\eta^2=0.57$), while dart throws were associated with higher mean (F1,11=19.84, p=0.001, partial $\eta^2=0.64$) and peak (F1,11=18.23, p=0.001, partial $\eta^2=0.62$) EMG amplitudes of THE. Moreover, the dart throws were associated with higher peak accelerations in x-direction (F1,11=22.27, p=0.001, partial $\eta^2=0.67$) and z-direction (F1,11=43.82, p<0.001, partial $\eta^2=0.79$) than underhand throws were. The timing of the EMG bursts differed significantly between techniques (Table 2). BIC activity (agonist burst) preceded TRI activity (antagonist burst) in underhand throws (Figure 3). This sequence was reversed (TRI→BIC) in dart throws, where TRI is the agonist and BIC the antagonist muscle. The deltoid muscle showed a triphasic EMG pattern (AD-PD-AD) particularly in dart throws (Figure 2, left panel). Since dart and underhand throws both involve shoulder flexion (supplementary figure 1), AD is an agonist and PD an antagonist muscle. The dominant hand’s maximum grip strength (38.7 ± 11.0 kg, mean ± SD) was significantly higher (t-test, p<0.01) than the strength of the contralateral hand (35.8 ± 9.6 kg).

We found several significant correlations between changes in throwing accuracy (Figure 1) and associated changes in EMG/acceleration parameters (Figure 4). Absolute values of the Pearson’s coefficients $r$ ranged between 0.3 and 0.66, indicating weak or moderate correlations. Better accuracy was associated with less THE muscle activity for both techniques and both sides (Figure 4A). Mean PD (antagonist) activity increased with better accuracy (Figure 4B) in three of the four conditions (D_DOM, D_NDOM, U_DOM). Finally, high peak wrist accelerations (x-direction) were associated with more accurate dart throws, but with less accurate underhand throws (Figure 4C).
Discussion

The present study analysed surface EMG recordings from shoulder, upper arm, and hand (THE, thenar) muscles to detect possible differences between the two sides in terms of muscle activation patterns during throws made by the dominant and non-dominant arms using two techniques (dart throw, underhand throw). The test persons were inexperienced, so effects of prior training can be excluded. As a main finding, the EMG curves of muscles of both upper limbs were nearly congruent regardless of the throwing technique (Figure 2). No significant interlimb differences of the mean and peak EMG amplitudes or peak accelerations were found (Table 1). Additionally, the timing of the EMG bursts was, with the exception of one muscle (PD), alike for the dominant and non-dominant arm in both throwing techniques (Table 2). The subtracted curves (difference DOM–NDOM, supplementary figure 3) showed only slight temporary deviations from the zero line, namely of the TRI and THE EMG activity, and of the acceleration along the x-direction (forearm long axis). These occasional deviations from zero do not pass rigorous post-hoc statistical evaluation with correction for multiple testing of data describing the different time points. Thus, the results speak in favour of motor equivalence in dart throwing with either arm as far as the EMG signals are concerned. The concept of motor equivalence (Bernstein, 1967; Schmidt, 1975) postulates that key features of the movement are specified by a superordinate motor program that activates spinal motor neurons in a specific temporal pattern of a certain strength regardless of the effector.

Considerable support for motor equivalence stems from studies that compared preferred and non-preferred limb movements, which analysed kinematics and kinetics, muscle activation (EMG), and also brain activation patterns (Rijntjes et al., 1999) during e.g., writing, pointing, aiming, and throwing. A recent review (Sherwood, 2014)
summarized the supporting evidence for motor equivalence of one- and two-dimensional aiming tasks performed with each arm, where the relative timing of velocity and acceleration peaks remained very similar for both upper limbs under various conditions (variations of direction, distance, speed, etc.). Less support for motor equivalence has been found for unconstrained throwing where, unlike in aiming and pointing, the hand does not decelerate when approaching a fixed target (Sherwood, 2014). Extensive practice seems to be required to achieve correspondence between kinematic patterns of both limbs in throwing (McDonald, van Emmerik, & Newell, 1989). Hore and colleagues reported that the dominant arm – but not the non-dominant – shows consistent differences between fast and slow throws in angular joint position space, suggesting interlimb differences of interjoint coordination (Hore et al., 2005). Morrison and Anson (1999) found a postponed onset of antagonist muscle activity during dart throws performed with the non-dominant hand in their EMG study of 12 volunteers. By contrast, the recent EMG study of Waterhouse (2014) reported no differences between the two sides in terms of arm muscle activations (biceps, triceps brachii) across four test persons, and concluded that throws performed by either arm are controlled by a common motor program.

In our study only a single timing variable differed significantly between limbs (Table 2), namely the onset of PD activity with a delayed start in non-dominant arm throws during both techniques (Figure 3). Antagonist activity slows down initial acceleration of the limb achieved during the first agonist burst (Berardelli et al., 1996; Morrison & Anson, 1999). The posterior deltoid (PD) is an obvious antagonist in underhand throws, since its contraction slows down the sweeping shoulder flexion accomplished by contraction of the biarticular biceps brachii (BIC) and anterior deltoid (AD) muscles. Dart throws also involve some shoulder flexion (supplementary figure
1); with AD activity preceding the onset of antagonistic PD bursts (Figure 3). In keeping with the delayed PD onset, the non-dominant hand tended to decelerate later than the dominant hand during dart throws (Figure 2). Higher mean PD activity was associated with better accuracy of dart throws (Figure 4B). However, the timing of other antagonistic muscles’ EMG bursts (BIC in dart throws, TRI in underhand throws) showed no significant interlimb differences. Likewise, Morrison and Anson (1999) described delayed non-dominant antagonist activation for the brachioradialis muscle only, but not for the biceps brachii in unconstrained (subject-determined) dart throws, and did not report interlimb differences of movement speed and duration. Hence, there is no general postponement of non-dominant antagonistic muscle activity in throwing. We think that the single significant timing difference (PD onset) found in the present comparison of dominant and non-dominant EMG curves is not compelling evidence against motor equivalence; the similarities of both sides prevail.

It might be interesting to investigate whether timing differences can be reproduced, not only in throwing but also in other tasks, such as kicking, pointing, and aiming, and under varying conditions (e.g., variations of speed and accuracy). Attentional focus may also play a role, since the shift from an internal focus on movement execution and kinaesthetic sensations to an external focus on action effects is known to improve accuracy and to reduce EMG activity (Lohse et al., 2010; Wulf, 2013). Unfamiliar movements of non-preferred limbs conceivably involve more explicit monitoring, i.e., an internal focus of attention.

Inverse dynamic analyses of reaching movements have revealed dominant arm advantages in the coordination of muscle torques across elbow and shoulder joints and in the control of limb trajectory dynamics (Bagesteiro & Sainburg, 2002; Sainburg,
A detailed kinematic analysis of throwing revealed interlimb differences in the coordination of shoulder, elbow, and wrist joint rotations when movement speed was varied (Hore et al., 2005). Moreover, Sachlikidis and Salter (2007) reported disparities between dominant and non-dominant arm throwing movements in high-performance cricketers by measuring three-dimensional kinematic variables; similar differences were also found in experienced team handball players (van den Tillaar & Ettema, 2009). Supporting evidence for motor equivalence of dominant and non-dominant arm movements therefore seems to depend on method and measures taken (Sherwood, 2014), and the amount of previous training of the preferred side has to be considered. Interlimb differences of dynamics and of kinematic parameters do not necessarily show up in the EMG curves of a limited number of selected muscles.

Unsurprisingly, accuracy of the dominant arm was significantly better in both throwing techniques in our study, as compared to the non-dominant arm. Performance of both sides improved, particularly during the first ten trials of the series of 30 throws (Figure 1). In a kinematic study of overarm throws with the trunk fixed, Hore and colleagues found that the exact timing of ball release has a decisive influence on throwing accuracy, since timing errors at the fingers are scaled up by the high angular velocity of the hand in space (Hore et al., 1996). The major cause of decreased throwing accuracy in the non-dominant arm was an increased variability in the timing of onset of finger extension (i.e. initiation of release) in their study. Expert dart players have smaller errors in release timing than novices or utilize hand trajectory patterns that can compensate for such errors (Nasu, Matsuo, & Kadota, 2014). We could not determine the exact moment of dart release in our investigation due to technical limitations of the equipment (video temporal resolution 20 ms, inadequate synchronisation with
EMG/acceleration data). Still, it is noteworthy that less EMG activity of hand muscles (THE) was associated with better accuracy regardless of the side (dominant, non-dominant) in both techniques (Figure 4A). In the dart throwing technique, mean THE activity of the dominant, more accurate hand tended to be lower than non-dominant THE activity, although this inter-manual difference did not reach significance (Table 1). Altogether the results suggest that a less forceful grip with less THE activity might facilitate precise timing of dart release and thereby improve throwing accuracy.

The cerebellum plays a key role in motor learning and in the temporal patterning of coordinated movement (Manto et al., 2012). The triphasic EMG pattern accompanying fast ballistic movements in humans originates as a sequence of “commands” issued from the motor cortex (Irlbacher, Voss, Meyer, & Rothwell, 2006), which is reciprocally connected with the cerebellum through prominent neuronal loops. Interestingly, antagonist EMG bursts were found to be delayed and reduced in cerebellar patients exhibiting hypermetric movements (Manto, 2009; Wild and Corcos, 1997), who are known to throw inaccurately due to a disordered timing of their finger opening (Timmann, Watts, & Hore, 1999). Whether in healthy persons the less accurate performance of the non-dominant upper limbs in targeted motor tasks can be explained by physiological differences between the two sides in terms of cerebellar control remains open to further investigation.

The present study is not without limitations. Only five EMG channels were available, limiting the number of muscles under study. The accelerometer, the main purpose of which was to detect movement onset and to trigger EMG recordings, was attached to the wrist for technical reasons. Thus the directions of its axes were not stationary, meaning that the spatial trajectory of the hand could not be reconstructed
unequivocally from its signals. Due to technical constraints we could not collect accurate kinematic data in parallel with the EMG recordings. The number of 30 throwing trials per condition was rather low compared to other studies that outlined the effects of extended practice on accuracy and kinematics of dart throwing (McDonald et al., 1989; Waterhouse, 2014). This study is deliberately focused on untrained persons, but it may nevertheless be of interest if and how EMG patterns and accuracy change with practice. For aiming tasks, it has been shown that changes in behavioural dynamics during motor learning involve a reorganization in muscular coordination patterns (Shemmell, Tresilian, Riek, Barry, & Carson, 2005; Vernooij et al., 2016).

In conclusion, we found that, in healthy inexperienced volunteers, the EMG curves of muscles of both arms are very similar during unconstrained unimanual throwing. This supports the concept of motor equivalence, with a common superordinate motor program specifying the timing and strength of agonist muscle activations of either limb.

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Declaration of Interest
The authors report no conflict of interest.
References


Timmann, D., Watts, S., & Hore, J. (1999). Failure of cerebellar patients to time finger opening precisely causes ball high-low inaccuracy in overarm throws. *J Neurophysiol, 82*(1), 103-114. doi:10.1152/jn.1999.82.1.103


Table 1. Throwing accuracy, EMG amplitudes and accelerations of dominant and non-dominant arm => see separate page

Table 2. Timing of EMG activity (burst onset and offset) of dominant and non-dominant arm during throwing => see separate page

Figure captions

Figure 1. Improvements of throwing accuracy during the series of 30 trials. Accuracy scores (i.e., target zone numbers) were averaged across participants for each trial of each series and condition. Data of the dominant arm (black dots) and the non-dominant (grey dots) arm are shown for dart throws (left graph) and underhand throws (right graph). Third-degree polynomials were fitted to the respective scatter plots.

Figure 2. Averaged EMG profiles and wrist acceleration curves of the dominant (black) and the non-dominant (red) arm. Mean values of the 12 participants, with error bars indicating inter-individual standard deviations. Data of dart (left panel) and underhand throws (right panel). Movement onset at time 300 ms (dotted vertical lines) was defined by an acceleration threshold (see methods). For difference curves (subtraction DOM minus NDOM) see supplemental material. Muscles: BIC, biceps brachii; TRI, triceps brachii; AD, anterior deltoid; PD, posterior deltoid; THE, thenar muscles of the hand.

Figure 3. Timing of muscle activations. Vertical bars denote mean onset and offset times of EMG bursts of muscles of the dominant (black bars) and the non-dominant (grey bars) upper limb. Dart (left panel) and underhand throws (right panel). Asterisks indicate the significantly (p<0.05) delayed PD onset on the non-dominant side. For abbreviations see Fig. 2.
Figure 4. Correlations between accuracy scores of the 30 trials (y-axes) and EMG / acceleration parameters (x-axes). Data of the dominant (black dots) and non-dominant side (grey squares) for dart (left panel) and underhand throws (right panel). A) Less THE activity was associated with higher accuracy in all conditions. B) Stronger PD EMG activity was associated with better accuracy in three conditions (D_DOM, D_NDOM, U_DOM). C) Accuracy of dart throws increased, precision of underhand throws decreased with peak wrist acceleration (x-direction). Pearson’s correlation coefficients r were significant (p<0.05) unless denoted ns (not significant). Regression lines were fitted to the scatterplots.

Three further (supplementary) figures with captions are provided as supplemental material in a separate pdf-file.
Public Interest Statement

Physical activity is a good way to improve health. Many sports require targeted throwing movements, for example handball, baseball, boules games and darts. It is relevant to know how such movements are controlled. We used electromyography to record shoulder, arm and hand muscle activity in untrained healthy volunteers who threw series of darts with their dominant hand and their non-dominant hand. Throwing accuracy of the dominant arm was significantly better, as compared to the non-dominant arm. Despite this difference, the muscle activation patterns of both upper limbs were nearly congruent and seem to be predetermined. Less activity of hand muscles was associated with better throwing accuracy. It is not necessary to focus on shoulder and arm muscle contractions when accurate throwing is practiced. Better grasp the dart (or ball) lightly and focus on the goal and on the timing of release. Training strategies may take this into account.
Johann P. Kuhtz-Buschbeck is senior assistant professor at the Institute of Physiology at Kiel University (Germany). His main research interest is human sensorimotor control and includes analyses of gait, of fine hand motor skills (precision grip) and targeted movements. A related previous kinematic study from his lab compared reach-to-grasp movements of the dominant and non-dominant hand. Patrick Keller (MD) is doctoral candidate at the Institute of Physiology (Kiel University).
Table 1. Throwing accuracy, muscle activity and accelerations of dominant and non-dominant arm

<table>
<thead>
<tr>
<th>Side</th>
<th>Technique</th>
<th>Dart throws</th>
<th>Underhand throws</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dominant</td>
<td>non-dominant</td>
</tr>
<tr>
<td>Throwing accuracy [range: 1 - 7]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average scores</td>
<td>4.81 ± 0.60</td>
<td>*</td>
<td>4.25 ± 0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.27 ± 0.68</td>
<td></td>
</tr>
<tr>
<td>EMG amplitudes [%MVC]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean BIC activity</td>
<td>5.9 ± 2.6</td>
<td>ns</td>
<td>6.0 ± 3.9</td>
</tr>
<tr>
<td>Peak BIC activity</td>
<td>24.4 ± 14.9</td>
<td>ns</td>
<td>25.6 ± 26.5</td>
</tr>
<tr>
<td>Mean TRI activity</td>
<td>10.1 ± 2.6</td>
<td>ns</td>
<td>10.7 ± 3.1</td>
</tr>
<tr>
<td>Peak TRI activity</td>
<td>52.9 ± 17.0</td>
<td>ns</td>
<td>47.3 ± 13.5</td>
</tr>
<tr>
<td>Mean AD activity</td>
<td>18.2 ± 8.3</td>
<td>ns</td>
<td>22.6 ± 11.9</td>
</tr>
<tr>
<td>Peak AD activity</td>
<td>46.4 ± 17.8</td>
<td>ns</td>
<td>57.1 ± 22.1</td>
</tr>
<tr>
<td>Mean PD activity</td>
<td>10.5 ± 9.1</td>
<td>ns</td>
<td>11.3 ± 8.7</td>
</tr>
<tr>
<td>Peak PD activity</td>
<td>38.5 ± 21.3</td>
<td>ns</td>
<td>37.3 ± 23.9</td>
</tr>
<tr>
<td>Mean THE activity</td>
<td>15.8 ± 6.6</td>
<td>a)</td>
<td>19.2 ± 6.5</td>
</tr>
<tr>
<td>Peak THE activity</td>
<td>48.8 ± 17.6</td>
<td>ns</td>
<td>57.7 ± 19.7</td>
</tr>
<tr>
<td>Peak wrist accelerations [g]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x – direction</td>
<td>6.92 ± 2.54</td>
<td>ns</td>
<td>6.79 ± 2.30</td>
</tr>
<tr>
<td>y – direction</td>
<td>-2.23 ± 0.85</td>
<td>ns</td>
<td>-2.63 ± 0.75</td>
</tr>
<tr>
<td>z – direction</td>
<td>2.79 ± 0.78</td>
<td>ns</td>
<td>2.33 ± 0.56</td>
</tr>
</tbody>
</table>

Footnote: Means ± standard deviations of the individual means (n=12 persons; 30 trials per condition in each subject). * better accuracy of dominant arm (significant at p<0.01); # significant differences between throwing techniques (p<0.05). a) Trend towards lower dominant thenar EMG activity in dart throws (p=0.056). b) Initial acceleration in y-direction was negative during dart throws (radial→ulnar movement) and positive during underhand throws (ulnar→radial movement), see Fig. 2. The absolute values of the relevant peaks did not differ between techniques. c) Initial acceleration in z-direction was positive during dart throws (volar movement direction) and negative during underhand throws (dorsal movement component). The absolute values of the acceleration peaks differed between techniques.
Table 2. Timing of EMG activity (burst onset and offset)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Side</td>
<td>dominant</td>
<td>non-dominant</td>
</tr>
<tr>
<td>EMG burst onset and offset times [ms]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIC onset</td>
<td>263 ± 29 ns</td>
<td>241 ± 55 #</td>
</tr>
<tr>
<td>BIC offset</td>
<td>351 ± 30</td>
<td>332 ± 45</td>
</tr>
<tr>
<td>TRI onset</td>
<td>193 ± 18 ns</td>
<td>190 ± 26 ##</td>
</tr>
<tr>
<td>TRI offset</td>
<td>288 ± 22</td>
<td>299 ± 28 ##</td>
</tr>
<tr>
<td>AD onset</td>
<td>170 ± 28 ns</td>
<td>177 ± 35 ##</td>
</tr>
<tr>
<td>AD offset</td>
<td>418 ± 52 ns</td>
<td>414 ± 59 ##</td>
</tr>
<tr>
<td>PD onset</td>
<td>207 ± 19 *</td>
<td>224 ± 31 ##</td>
</tr>
<tr>
<td>PD offset</td>
<td>318 ± 29 ns</td>
<td>340 ± 30 ##</td>
</tr>
<tr>
<td>THE onset</td>
<td>173 ± 40 ns</td>
<td>178 ± 34 #</td>
</tr>
<tr>
<td>THE offset</td>
<td>335 ± 51</td>
<td>335 ± 27 ##</td>
</tr>
</tbody>
</table>

Footnote: Means ± standard deviations of the individual means (n=12 persons; 30 trials per condition in each subject). Onset and offset times of the EMG bursts were analyzed trial by trial (see methods). * Significant (p<0.05) timing difference between dominant and non-dominant arm. # Significant differences between throwing techniques (# p<0.05, ## p<0.01); with ANOVA F1,11 values of 8.1 (BIC onset), 222.3 (TRI onset), 135.6 (TRI offset), 34.3 (AD onset), 14.1 (AD offset), 33.3 (PD onset), 50.2 (PD offset), 9.4 (THE onset), 15.4 (THE offset). There were no significant interactions between hand (DOM, NDOM) and throwing technique.
Figure 1

Dart throws

Underhand throws

Accuracy (target zone)

DOM
NDOM

Series of throwing trials [1-30]
Figure 2

[Graph showing EMG activity and wrist acceleration for dart throws and underhand throws, comparing NDOM and DOM conditions.]
Figure 4

A) Dart throws

Accuracy [target zone] vs. Mean EMG activity of hand muscles (THE)

- NDOM: $r = -0.47$
- DOM: $r = -0.66$

B) Underhand throws

Accuracy [target zone] vs. Mean EMG activity of post. deltoid (PD)

- NDOM: $r = 0.54$
- DOM: $r = 0.50$

C) Peak wrist acceleration (x-direction)

Accuracy [target zone] vs. Peak wrist acceleration (x-direction)

- NDOM: $r = 0.57$
- DOM: $r = 0.43$