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*Muscle synergies in archery: an explorative study on experienced athletes with and without physical disability**

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***Abstract*— Archery technique requires a coordinated activation of shoulder girdle and upper extremity muscles to perform a successful shot. The analysis of muscle synergies can provide information about the motor strategy that underlies the shooting performance, also supporting the investigation of motor impairments in athletes with disability. For this purpose, electromyographic (EMG) data from five muscles were collected from a non-disabled and a W1 category Paralympic athlete, and muscle synergies were extracted from EMG envelopes using non-negative matrix factorization. Muscle synergies analysis revealed features of the motor strategy specific to the athletes' shooting technique, such as the contribution of the biceps muscle instead of the posterior deltoid during the arrow drawing and target aiming in the Paralympic athlete compared to the non-disabled athlete. It is concluded that the evaluation of the muscle synergies may be a valuable tool for exploring the motor strategies adopted by athletes with disability, providing useful information to improve athletic performance and possibly prevent the risk of injury.**

***Clinical Relevance*— The investigation of muscular activation patterns during the athletic gesture of an elite archer could lay the foundations to the understanding of muscle synergy involved in the gesture that might be specific to athletes with (and without) disability. Such knowledge would provide support to the coach and the athlete during the training sessions to improve the performance and reduce the risk of injuries.**

I. Introduction

Archery shooting technique involves a sequence of movements which is consistently repeated over time. Each shoot cycle can be described through specific phases: once on the shooting line, the archer raises the bow, pulls the bowstring, aims at the target and releases the arrow [1]. Each of these movements is performed through a coordinated activation of the upper limb muscles. Specifically, electromyographic (EMG) analysis revealed an active involvement of posterior deltoid and trapezius muscles during the pulling of the bowstring [2], with the lower trapezius muscle recruited for the scapular fixation [3]. On the bow-side, scapular muscles (deltoid, trapezius) are responsible for the stabilization of the humeral tremor to improve aiming precision [4]. Despite the cited studies investigated the activity of the above-mentioned muscles individually, the reported results seem to suggest that a distinct neural organization of these muscle activation patterns underlies the shoot cycle motor task and its specific phases. When performing a movement, the central nervous system (CNS) simultaneously activates small muscle groups [5], known as muscle modules, in order to decrease the complexity of an extremely redundant problem (the number of muscles is definitely higher than the number of degrees of freedom) [6]. These modules are commonly named muscle synergies [7-9], and reflect the coherent activation, in space and time, of a specific group of muscles [10]. Muscle synergies are usually extracted from EMG patterns through factorization methods. Among these, the non-negative matrix factorization (NNMF) is considered the most appropriate for identifying muscle synergies in dynamic tasks with different levels of muscle contraction [11]. In recent years, the analysis of muscle synergies has been applied also to the sport performance field: the distribution of muscles' relative weight in the synergy space, in fact, may contribute in understanding the neuromechanical aspects of the considered movement, especially in those disciplines requiring a precise neuromuscular control [12]. Muscle coordination in performing repetitive voluntary movements is strongly influenced by long-term training [13], with the CNS continuously making adjustments to optimize the selection of muscle synergies that are best suited for the specific movement [12]. In this light, the identification of muscle synergies in experienced athletes can be exploited for the characterization of skill patterns developed with training [14, 15] and as a reliable method to better understand the motor control mechanisms of individuals affected by movement disorders [16]. In fact, adaptations of the CNS are evident in athletes suffering from disrupted motor control, where compensatory strategies are activated to optimize motor-skills and maximize performances [17, 18]. In this context, the investigation of the archery shooting movement is of large

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interest, considering that accuracy and repeatability are two fundamental requirements for achieving successful outcomes [19]. In addition, despite the growing participation in this discipline [20], up to date the scientific interest concerning archery and athletes with disability is minimal. Therefore, the aim of this study is to investigate the EMG activation patterns and muscle synergies of both a Paralympic archer and an experienced archer without disability. Due to the small sample size, the purpose of the work is not to obtain general conclusions related to the athletes' shooting techniques, but to understand whether the investigation of muscle synergies could be a valuable method for exploring the motor strategies adopted by the athletes.

II. Methods

One non-disabled experienced athlete (47 years, male) and one Paralympic athlete (34 years, male, W1 category), both with more than 10 years of experience in archery, participated in the study (approved by University of Rome "Foro Italico" Institutional Review Board: CAR 74/2021). The athlete with disability was affected by spina bifida and spastic tetraparesis, with impaired motor control of both upper limbs (particularly at the right side) and no control of lower limbs, thereby carrying out the experimental protocol on a wheelchair. The non-disabled athlete performed the test in a standard standing position. Both athletes performed the shooting by using the left arm to hold the bow (bow side) and the right arm for drawing the arrow (draw side). Both archers shot three ends of six arrows at a target positioned at a 10-meter distance from the shooting line. A motion capture system (Vicon, UK) was used to track the 3-dimensional trajectory of two markers attached on the ulnar and radial styloid processes of both wrists and further used to perform the shoot cycle phase segmentation by identifying the following events: initial bow raising, maximal bow raising, full-draw, arrow release and bow lowering. A synchronized surface EMG device (MiniWave, Cometa, IT, sampling rate 1000 Hz) was used to register the activity of the following muscles: anterior deltoid (AD) and upper trapezius (UT) muscles of the bow side, and biceps (BI), posterior deltoid (PD) and upper trapezius muscles of the draw side. Raw EMG signals were band-pass filtered (30-400 Hz), full wave rectified and low-pass filtered at 6 Hz with a zero-lag 4th order Butterworth filter to obtain EMG linear envelopes [8]. The filtered EMG signals from each shoot cycle (i.e., from initial bow raising to bow lowering) were normalized to the mean EMG peak amplitude across multiple shots obtained for each muscle and then time-normalized to 200 points. Time- and amplitude-normalized EMG linear envelopes were also averaged across multiple shots within each participant for qualitative analysis. Muscle synergies were extracted from EMG envelopes using the NNMF algorithm (available in the Matlab(R) software, Mathworks, US). Reconstructed EMG patterns are based on the linear combination of the muscle synergy weights (W) and the activation coefficients (C) as follows:

$$EMG_R = WC + e, \tag{1}$$

where EMG_R is a L x N matrix representing the muscle activation patterns of L muscles at N time instants, W is a L x K matrix representing the time-invariant contribution of each muscle in each of the K synergies, C is a K x N representing the time-dependent activation coefficient matrix, and e is a L x N matrix representing the reconstruction error at each time instant for each muscle. The algorithm is based on iterative updates to minimize the mean square error between original and reconstructed muscle activation patterns. In order to avoid local minima, the algorithm was repeated 50 times for each subject [21]. The number of synergies was determined as the minimum number of synergies for which the variance accounted for (VAF) was ≥ 97%. VAF is described by the following equation:

$$VAF = \frac{||(EMG_R - W*C)^2||}{||EMG_R||^2} \tag{2}$$

For a more objective assessment of the differences between the time distribution of the synergy weights of the two athletes, the cross-correlation (CC) was computed for each synergy using the activation coefficient signals.

III. Results and Discussion

A. Electromyographic Analysis

The two archers performed the shooting action with different relative timings of the events (maximal bow raising, full-draw and arrow release) within the shoot cycle, thereby displaying different muscle activation profiles (Fig. 1). In particular, for what concerns the bow side, the non-disabled athlete displayed an initial activation of the shoulder muscles during the bow raising, which was maintained in the AD and slightly decreased in the UT during the target aiming and after the arrow release. The athlete with disability showed a similar initial increase in both the AD and UT muscles activity during

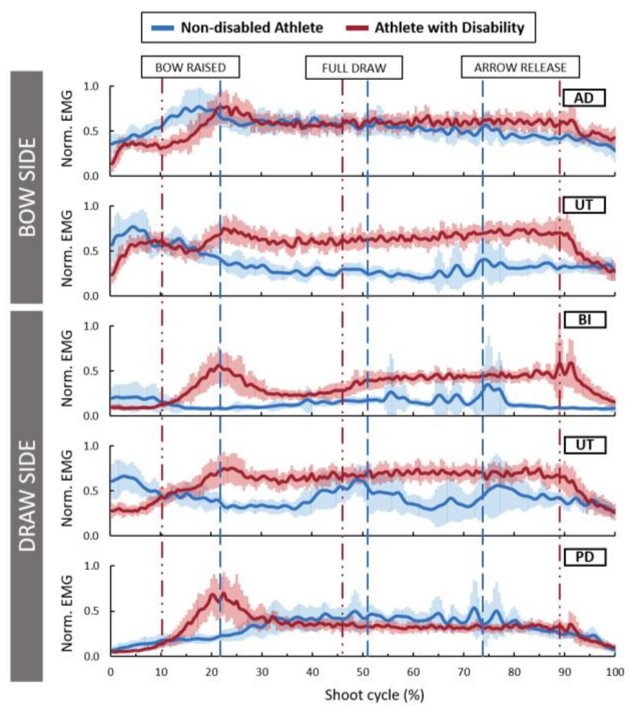

Figure 1: Ensemble average of the amplitude-normalized EMG linear envelopes of the bow side and draw side muscles from each athlete expressed as percentage of the shoot cycle. Shaded areas represent ±1 standard deviation across multiple shoots. Vertical lines indicate events of the shoot cycle averaged across multiple shoots per each athlete.

the bow raising, followed by a second burst and a sustained overall muscle contraction up to the arrow release. On the draw side, the non-disabled athlete activated the UT during the bow raising and, subsequently, gradually increased and sustained the PD activation during the arrow drawing and target aiming. The activity of the BI was not predominant in any of the shooting phases, but presented a little burst at the arrow release moment. In contrast, the athlete with disability displayed an EMG burst of the UT, BI, and PD muscles at the beginning of the arrow drawing movement, followed by an overall muscle activation during the aiming and up to the arrow release. The analysis of the muscle activation profiles yielded some similarities between the two athletes. Indeed, consistently with the existing literature, both athletes showed an increased activation of AD and UT muscles of the bow side during the bow raising, as well as of UT and PD of the draw side during the arrow drawing and target aiming [3, 4]. These sustained muscular activations, especially that of the PD, are responsible for the arm stabilization and the tremor reduction while aiming at the target [4]. Interestingly, the Paralympic athlete displayed the overall contraction of the bow side muscles until the arrow release, which is crucial for reducing the shoulder mobility and tremor through scapular stabilization [3, 4]. On the draw-side, another aspect peculiar to the athlete with disability was highlighted by the BI activity: while the non-disabled athlete showed only unstructured activations [3], the athlete with disability displayed a sustained BI contraction while drawing and aiming at the target. A possible explanation comes from the shooting technique of the draw arm adopted by the Paralympic athlete: during the pulling of the bowstring, the elbow was flexed with a low degree of arm elevation, which is peculiar compared to the 90° angle of arm elevation previously reported in the literature [4]. As a consequence of this motor strategy, likely adopted to compensate for the impaired motor control of the upper limb, a higher involvement of the BI was observed in the Paralympic athlete.

B. *Muscle Synergies*

The NNMF analysis of the EMG envelopes resulted in the extraction of three main muscle synergies for both athletes. The first synergy was characterized by the bilateral activation of UT in both athletes and, additionally, a minor contribution of the DA of the bow side in the Paralympic athlete only (Fig. 2, top panel). The cross-correlation computed across the activation coefficient waveforms revealed a slight difference between the athletes (CC: 0.87). In fact, while the muscles activation was consistent during the bow raising and aiming phases, the contribution of the synergy during the drawing phase was appreciable only for the athlete with disability. This is in line with the results from the EMG signals, that revealed a burst of the bow side muscles in correspondence of the bow raising movement for both the athletes, but a diversification of the UT pattern during the drawing movement. Therefore, this muscle synergy could explain the involvement of the UT muscle during the initial elevation of the upper limbs and the further stabilization of the humeral-scapular joints of both the bow and draw sides. The second muscle synergy showed a main contribution of the draw side AD and bilateral UT in both

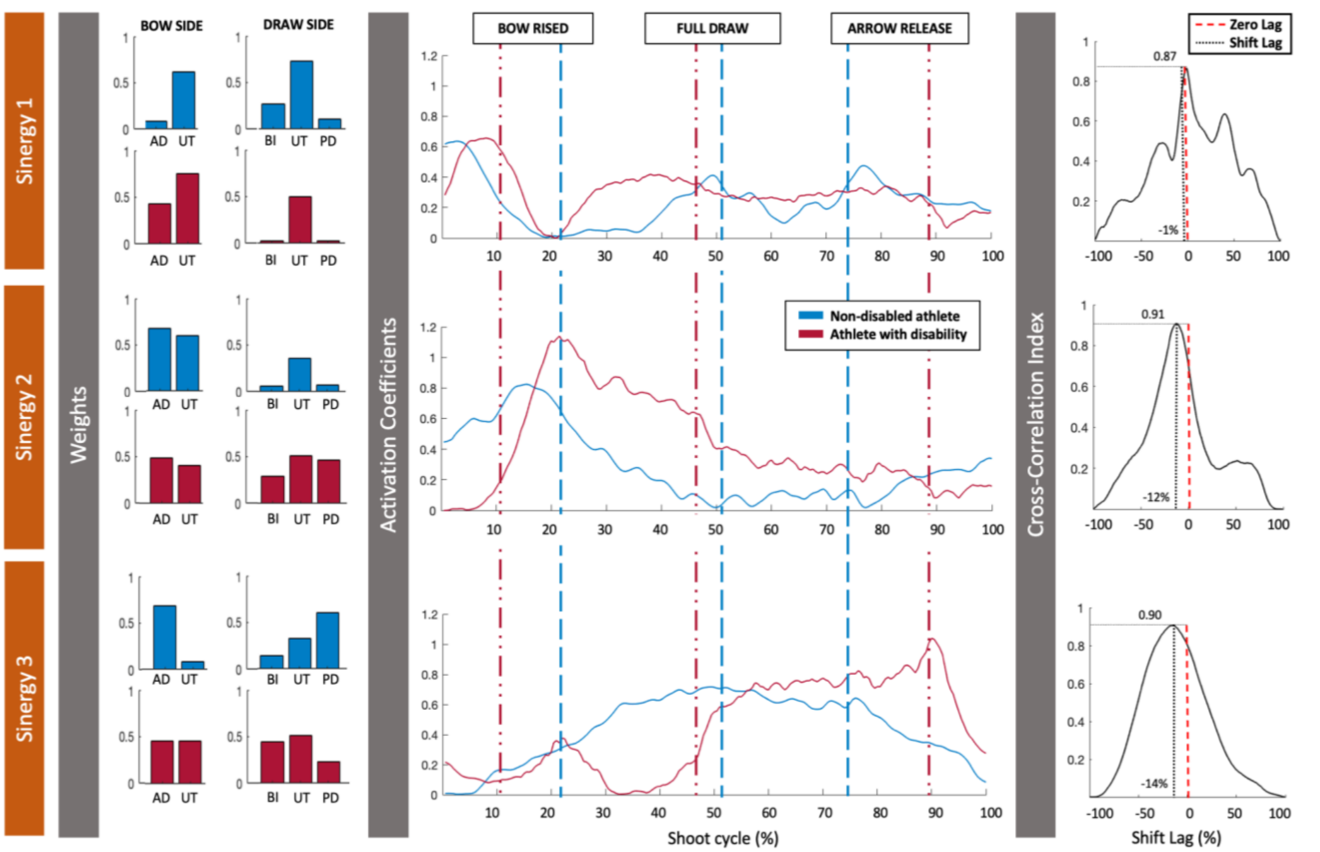

Figure 2: Muscle weights (left panel) and activation coefficients (middle panel) of the three muscle synergies extracted by the NNMF analysis from the EMG envelopes of the non-disabled athlete (blue) and the athlete with disability (red). Cross-correlation analysis (right panel) between the muscle activation coefficients of the non-disabled athlete with respect to the Paralympic athlete are plotted against 100% phase lag (positive and negative) with respect to the entire signal; maximum CC value and corresponding phase lag are explicated.

athletes, with an additional involvement of the BI and PD of the draw side in the Paralympic athlete only, (Fig. 2, middle panel). The CC indicated a high correlation between activation coefficient waveforms (CC: 0.91) with a consistent time shift of the non-disabled athlete with respect to the athlete with disability (shift lag: -12%). Interestingly, this phase lag was similar to the difference in the relative timing of the maximal bow raising between the two athletes (22±2% and 10±1%, respectively). However, despite the similar shape of the waveforms, the peak of the initial increase in the muscular activation coefficients was respectively observed before and after the instant of maximal bow raising in the non-disabled athlete and in the athlete with disability. Thus, this muscle synergy seems to be involved in the bow raising movement for what concerns the non-disabled athlete, whereas may be responsible for starting the arrow drawing motion in the Paralympic athlete. Finally, the third synergy was mostly referred to the arrow drawing and target aiming (Fig. 2, bottom panel). From the beginning of the drawing movement up to the arrow release, the athlete without disability exploited the AD likely to sustain the bow weight and stabilize the arm, whereas the Paralympic athlete displayed a shared contribution between the AD and UT muscles. On the draw side, the muscle synergy involved a predominant activity of the PD in the non-disabled athlete and of the BI in the athlete with disability. The CC indicated a good correlation across the signals (CC: 0.90) with a remarkable temporal shift (shift lag: -14%). However, the analysis of the activation coefficient waveforms revealed a partially different functional role of the synergy between the two athletes. In fact, while this muscle synergy was mainly involved during both the drawing and aiming periods in the non-disabled athlete, its contribution was predominant during the target aiming in the athlete with disability. This difference could be ascribed to the shooting technique of Paralympic athlete and the different behavior of the draw arm previously reported from the analysis of the EMG activation patterns, which specifically involved a major contribution of the BI muscle with respect to the PD. The main difference between the two athletes in terms of muscle synergy contribution in the different phases of the shooting task is related to the drawing movement. In fact, while for the non-disabled athlete the muscles activated to pull the bowstring expressed their contribution only in the third synergy, for the Paralympic athlete the draw contribution was shared between the second and the third synergy. In particular, the peculiar burst displayed by the BI, and also observed in the other muscles, around the 20% of the shoot cycle, matched the peak of the activation coefficient of the third muscle synergy. Another interesting difference concerns the recruitment of the bow side muscles during the whole shoot cycle: both athletes performed the bow rising movement using the UT (first synergy) and stabilizing the bow arm using both the AD and UT, with a slight predominance of the AD (second synergy). However, from the beginning of the drawing movement, the non-disabled athlete sustained the bow load only using the AD, therefore relieving the UT. Differently, the Paralympic archer kept bearing the weight with both the muscles (third synergy). These discrepancies may be due to the differences in terms of execution technique (arm angle position) and posture (seated vs standing) which characterized the athletes' shots. Muscle synergies analysis allowed to get insights of the muscles' functional role during the different phases of the shooting from a rather different viewpoint with respect to single EMG pattern analysis. Besides revealing some common behaviors between the athletes, this analysis was able to discriminate those compensatory strategies adopted by the athlete with disability, such as the BI activation during the pulling of the bowstring or the involvement of the UT for supporting the bow weight throughout the shooting gesture.

IV. CONCLUSIONS

The investigation of muscle activation patterns of athletes with disability provides relevant information for understanding the role of motor impairments in the execution of sports motor tasks. In this context, the analysis of muscle synergies represents a useful tool for understanding the motor dysfunction and the consequent compensatory strategies implemented to optimize skills and maximize performances.

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