Electromyographic and kinematic evaluation of bench press exercise: a case report study on athletes with different impairments and expertise

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Abstract
Purpose With an increase in the number of adapted sports, the need to monitor sports performance in people with different abilities has grown. Indeed, a thorough evaluation of the sports gesture could prevent the occurrence of injuries, enable a continuous performance assessment, and allow to verify the compliance of the requirements for the competitions. Gesture kinematics provides an assessment of performance, while the muscle activities reveal the underlying strategies adopted by each athlete. In this context, we propose an instrumented evaluation to assess performance in Para-powerlifting. Our goal is to define and test a setup and a protocol to quantitatively assess the execution of bench press exercise in athletes with different abilities.

Methods We recruited an unimpaired athlete and three Paralympic athletes. They were requested to execute the bench press exercise while we recorded muscle activity and kinematic data from the upper body. We investigated the sport gesture by extracting parameters describing coordination, symmetry, and synchronism between arms, and motor variability while repeating the gesture.

Results Paralympic athletes performed the gestures with higher coordination between arms and low variability across repetitions compared to the unimpaired athlete, who was not at the Olympic level. All participants obtained similar kinematic performance by adopting different muscle strategies.

Conclusions This study is a proof of concept that the instrumented evaluation proposed here can allow to conduct a complete assessment of the bench press exercise, in terms of kinematics, muscle activity and performance in athletes with different abilities.

Keywords Bench press · Paralympic athletes · Muscle strategies · Sensorimotor disabilities

Introduction
The number of people with disabilities involved in sports and physical activities is rapidly increasing. Studies have shown that active participation in sports has a positive impact on the quality of life of people with disabilities by promoting personal health (mental and physical wellbeing), stimulating individual development (increase in self-confidence and improved self-esteem) and enabling social interaction, inclusion and integration [1–3]. These are probably the reason behind the recent growth of adapted sports and the increase in the number of para-athletes. Indeed, more than 4000 athletes from 162 nations competed in the last Paralympic Games (Tokyo 2020–2021) which set a worldwide record for the highest number of athletes in a game.
With the growth of people with disabilities involved in sports, there has been a concurrent increase of interest in investigating the potential benefits and effects of sports practicing in impaired athletes [4]. More in detail, the rise of adaptive sports has intensified the need to define methods to perform a qualitative and quantitative assessments of the athlete’s motor performance to assist both the athlete in itself and the coaches in enhancing training and optimizing the athletic gesture.

Here, we started to address this need, by proposing an instrumented evaluation to assess performance in powerlifting and Para-powerlifting, an adaptation of powerlifting for athletes with disabilities that consists of a single discipline, the bench press.

Competed at the Paralympic games since 1984, Para-powerlifting is open to any athlete with a minimum level of disability (paralysis, lower limb amputations or cerebral palsy) who can extend their arms within 20° of full extension. During competitions, athletes lie on their back on a bench—with a body configuration that depends on the subject’s disability [5]—with the barbell grasped in both hands. The gesture is then executed in two phases: an eccentric and a concentric phase. During the eccentric phase, athletes perform a downward movement by lowering the barbell to the upper torso and holding it motionless on their chest. During the concentric phase, athletes perform an upward movement by raising the barbell, with an equal symmetry and synchrony of the upper limbs, up to their maximum and complete extension [5]. The barbell does not have to be completely horizontal when extending the arms, but there must be an equally timed lockout of both arms at the end of the upward movement.

Due to its structure, the bench press gesture requires the athlete to perform a short but highly intense effort [6] with the recruitment of multiple muscles. The pectoralis major, deltoids and triceps are usually used to press the bar vertically, the biceps act as dynamic stabilizers, while the trunk muscles are recruited to maintain a stable position on the bench.

To date, few studies have investigated this gesture in impaired [7] and unimpaired [8] as well as in novice and elite athletes [6, 9]. However, to the best of our knowledge, a comprehensive evaluation including both kinematic and muscle activations has not been yet proposed.

The aim of this study is to test an instrumented setup, protocol and set of parameters developed and selected to provide an objective and thorough evaluation of the bench press gesture performance, muscle activity and kinematics in athletes with different abilities. To prove that the evaluation proposed is capable of offering a complete characterization of the bench press gesture regardless of the disability or ability of the athlete tested, we conducted a series of case reports where we tested the setup and protocol on a heterogeneous group of athletes, i.e., athletes with different types of abilities/disabilities. Specifically, we evaluated the performance and the kinematic-muscle strategies of the bench press gesture of four elite athletes: an able-bodied athlete and three Paralympic athletes with different types of motor impairments.

Materials and methods

Subjects

This study includes a series case reports conducted on four bench press athletes with different physical abilities. S1 (male, 22 years) was an able-bodied athlete; S2 (female, 20 years) had an incomplete spinal cord injury at the level of D10–D11 from birth. S2 presented a scar on the spinal cord with a spinal stenosis, three flattened intervertebral and, consequently, a spastic left lower limb. S3 (male, 29 years) had a mid-third amputation of his left leg thigh and a nerve injury at his right leg. S4 (male, 40 years) had a spinal lesion at the level of the third dorsal segment, classified as ASIA C from the American Spinal Injury Association, and was in a chronic condition (years after injury: 15). All subjects had no cognitive impairment and are elite powerlifters; more precisely S2, S3 and S4 are Paralympic athletes.

The study conformed to the 2013 Declaration of Helsinki and all participants signed an informed consent to the analysis and publication of their data for research purposes.

Experimental setup and protocol

The evaluation session was performed in the Movement Analysis Lab at Santa Corona Hospital, Pietra Ligure (SV, Italy). Subjects executed the bench press exercise as in the competitions: the positioning of subjects was different for athletes with and without disabilities. Specifically, all the athletes lay down on the bench for the whole duration of the movement, but the able-bodied athlete kept the feet motionless and in contact with the ground (Fig. 1a), in complete plantar support during the whole test while the others adopted the supine position, with legs and feet stretched out on the regulatory bench (Fig. 1b). In the latter case, belts were used to fix the thighs and the ankles to the bench, to ensure the stability of the lower limbs during the task. All athletes performed the same task: they grasped the barbell with both hands, they lowered it to the upper torso, paused, and then they pressed the barbell upwards, extending their arms until reaching their maximum extension. Before the experiment, subjects were tested to determine their bench press one-repetition maximum (1RM, i.e., the maximum weight they could lift for one single repetition). During the experiment, they performed the exercise at 90% of their...
1RM. After a warm-up phase, each subject repeated the exercise three times with three minutes breaks within repetitions. Each subject lifted a different weight depending on their gender, body-weight and 1RM (S1: 80 kg, S2: 60 kg, S3: 120 kg, S4: 90 kg). According to [10], taking into consideration the body-weight when selecting the lifting weight should account for gender differences between the athletes.

Data acquisition

During the experiment, we recorded both muscle and kinematic data. We collected kinematic data with a motion capture system (SMART DX, BTS Bioengineering, Milan, Italy) that included eight infrared cameras, with reflective spherical passive markers (15 mm diameter). Data, sampled at 100 Hz, reflected the position of 12 markers (Fig. 1c): four were placed on the barbell (two per side, one externally, on the edge of the barbell and the other internally, 45 cm far from the edge) and eight on the subject to record on both sides the kinematic of the wrist, elbow, shoulder, and hips. Specifically, markers were placed bilaterally over the ulnar styloid process, the lateral epicondyle of the elbow joint, the acromion and over the anterior superior iliac spine. Electromyographic data were recorded with surface electromyography (sEMG) with a sampling frequency of 1000 Hz (acquisition system: FREEEMG300, BTS Bioengineering, Milan, Italy). Data were bilaterally collected from the following muscles: Trapezius, Anterior deltoid, Pectoralis major, Biceps, Triceps brachii, and Rectus abdominis.

The surface electrodes were placed in accordance with the recommendations of SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) of the Biomedical Health and Research Program (seniam.org). The sEMG and kinematic data were hardware synchronized and both have been first processed with Smart Tracker (BTS Bioengineering, Milan, Italy) and then on Matlab (MathWorks, Natick, MA, USA).

Data analysis

Markers’ data were smoothed with a 4th-order Savitzky–Golay filter with a cutoff frequency of 12 Hz. Raw sEMG data were filtered between 20 and 450 Hz [11], then rectified and filtered again with a low pass 4th-order Butterworth filter with 4 Hz cutoff frequency to obtain the signal envelopes. We segmented each signal based on the movement speed of the inner barbell. We considered the start of a movement trial as the start of the eccentric phase (the barbell is moved downward), and the end of the movement trial as the end of the concentric phase (the barbell is moved upward). The thresholds for identifying the start and the end of the movement were set at 10% of the corresponding maximum peak speed, respectively the maximum speed of the eccentric and the concentric movements. Specifically, the start of the movement trial was defined as the first time instant the speed exceeded the first threshold and the end of the movement trial was defined as the first time instant the speed dropped below the second threshold after the maximum flexion of the arms [12, 13].

For the analysis of both kinematic and sEMG data, we considered a window starting 50 ms prior to the start and ending 50 ms after the end of the movement trial. Kinematic and sEMG data of each movement trial were time-interpolated over a time base with 101 points [14], to be compared independently on time.

The position of the electrodes did not change during the entire acquisition allowing for direct comparisons among all movements of a muscle for each subject. To compare sEMG data from different subjects and between the two sides of the body of a same subject, we normalized the sEMG envelopes.
for their median value [15, 16] computed over all the data collected from each subject.

As for the kinematic data, we qualitatively evaluate the movements in the sagittal, frontal, and transverse planes and to quantitatively assess performance, we computed:

- The duration of eccentric and concentric phases of the movements, expressed in seconds and percentage.
- The repeatability within repetitions, as the Pearson’s correlation coefficient and the lag between the three repetitions.
- The lateral symmetry computed as the Pearson’s correlation coefficient and lag between left and right markers’ trajectories.

As for the sEMG normalized envelopes, we displayed the muscle activation patterns of each subject together with the variation of the elbow angle (the angle between the shoulder, elbow and wrist markers), to understand the phase of the movements where each muscle was active.

Then, to quantitatively assess muscle activity, we computed:

- the root mean square (RMS);
- the normalized value of the maximum peak (MP) [17];
- the peak time value expressed as a percentage of the movement trial (TP%) [17];
- the interval of activation as the temporal intervals in which muscles were active. To compute the onset and offset of muscles’ activation, we used the nOptim method [18];
- the left–right symmetry, as Pearson’s correlation coefficient and the lag within left and right muscle activations.

**Results**

All subjects succeeded in performing the three bench press movements. S2, S3 and S4 had perfect overlapping trajectories on the three planes (Figs. 2, 3 and 4), with comparable timing for the upward and downward movements (Table 1). Instead, S1 performed the first repetition with a different timing. In his first movement, the concentric phase was more than 1 s longer (66% of the total movement) than the same phase in the other two repetitions (51.5–54.5%), while the eccentric one lasted approximately the same.

In the frontal and transverse planes (Figs. 3 and 4), the barbell and wrist displacements were small and not significant. Instead, as expected, left and right elbows (Fig. 4) moved in the opposite direction but, curiously, each subject had its own strategy. More precisely, S1, S3 and S4 tented to bring the elbow closer to the chest at the end of the eccentric movement, while S2 laterally opened the elbows at the beginning of the eccentric phase to reclose them only at the end of the concentric one. However, all those strategies allowed the subjects to complete the task.

The kinematic parameters (Tables 2 and 3) confirmed what we observed from the trajectories, the movements’ repeatability is high as well as the left–right symmetry, with a negligible lag.

As for the sEMG envelopes, muscle activations are reported in Fig. 5 together with the elbow angles.

The trapezius, which has the role of raising-lowering-adducts and externally rotating the scapula, was active for all subjects for the whole duration of the movement with a maximum activation peak between the end of the eccentric phase and the beginning of the concentric phase (40–60%, Table 4).

The deltoid, the pectoralis, and the triceps muscles, crucial to perform the upward movements, were more active for all subjects in the concentric part of the gesture. The
The maximum activation peak was at the beginning of the concentric phase and had comparable amplitude between participants (Table 4). However, the activation of those muscles already started in the eccentric phase of the movement, but with different amplitude for each subject. More precisely, the deltoids of all subjects became active from the 10–20% to almost the end of the total movement, with the bigger

Table 1  Eccentric (Ecc.) and concentric (Conc.) movement duration for each repetition (T1, T2 and T3) expressed in (a) seconds (s) and (b) percentage (%)

|       | S1 Ecc | S1 Conc | S2 Ecc | S2 Conc | S3 Ecc | S3 Conc | S4 Ecc | S4 Conc |
|-------|--------|---------|--------|---------|--------|---------|--------|---------|
| (a)   |        |         |        |         |        |         |        |         |
| T1    | 1.68   | 3.37    | 1.57   | 1.62    | 1.85   | 2.13    | 1.55   | 1.96    |
| T2    | 1.73   | 1.86    | 1.69   | 1.64    | 2.06   | 2.21    | 1.80   | 1.89    |
| T3    | 1.72   | 2.07    | 1.63   | 1.60    | 2.02   | 2.32    | 2.84   | 2.02    |
| (b)   |        |         |        |         |        |         |        |         |
| T1    | 34.0   | 66.0    | 49.5   | 50.5    | 46.0   | 54.0    | 43.5   | 56.5    |
| T2    | 48.5   | 51.5    | 51.5   | 48.5    | 48.0   | 52.0    | 49.5   | 50.5    |
| T3    | 45.5   | 54.5    | 50.5   | 49.5    | 46.5   | 53.5    | 48.0   | 52.0    |

Fig. 3  Elbow, wrist, and barbell marker trajectories (respectively, one in each row) on the frontal plane for each subject (a subject in each column). Red and blue lines represent the right and left side of the body, respectively. Darker lines represent the first repetition and lighter lines the last.

Fig. 4  Elbow, wrist and barbell marker trajectories (respectively, one in each row) on the transverse plane for each subject (a subject in each column). Red and blue lines represent the right and left side of the body, respectively. Darker lines represent the first repetition and lighter lines the last.
contribution in the concentric phase; the activations were more stable for all Paralympic athletes.

The pectoralis and the triceps muscles of S1 were active only in the concentric phase of the movement, while S2, S3 and S4 activated them also in the first phase of the movement (10–30% of the movement, Fig. 5), although S3 and S4 to a minor extent. In addition, for S2 the amplitude of the activation of the triceps in the two phases of the movement was similar; instead, S3 and S4 had a bigger amplitude in the concentric phase. Moreover, both S1 and S3 exhibit higher MP and RMS compared to S2 and S4 (Tables 4 and 5).

The rectus abdominis muscles and the biceps muscles displayed different activation patterns across subjects, with also a different timing. While for S2, S3 and S4, the rectus abdominis was active in the concentric phase, S1 activated the rectus during the whole movement, with MP and RMS lower than the other individuals (Tables 4 and 5). As for the biceps, the activations differed among participants. More precisely, for S1 the biceps were mainly active in the first phase of the movement, with an MP at about 28% of the cycle; in S3 and S4, they were active from the middle part of the eccentric movement to the first part of the concentric movement with MP respectively at about 55% and 51% of the cycle; and in S2, the biceps were active for all the movement duration with an MP at about 76% of the trial. Furthermore, S1 had significantly higher MP for

| Marker | S1 | S2 | S3 | S4 |
|--------|----|----|----|----|
| Elbow  | 0.84 ± 0.03 | 0.82 ± 0.01 | 0.93 ± 0.00 | 0.86 ± 0.01 |
| Wrist  | 0.99 ± 0.01 | 1.00 ± 0.00 | 1.00 ± 0.00 | 0.99 ± 0.00 |
| Balancer | 0.97 ± 0.02 | 1.00 ± 0.00 | 0.99 ± 0.00 | 0.98 ± 0.01 |

![Table 2](image)

Table 2 Left and right symmetries of the elbow, wrist and balancer movement expressed as Pearson’s correlation coefficient (R, mean ± std)

Table 3 Repeatability of the elbow, wrist and balancer movement expressed as Pearson’s correlation coefficient (R, mean ± std)

| Marker | S1 Right | S1 Left | S2 Right | S2 Left | S3 Right | S3 Left | S4 Right | S4 Left |
|--------|---------|---------|---------|---------|---------|---------|---------|---------|
| Elbow  | 0.90 ± 0.08 | 0.89 ± 0.09 | 1.00 ± 0.00 | 1.00 ± 0.00 | 1.00 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 |
| Wrist  | 0.89 ± 0.09 | 0.88 ± 0.10 | 1.00 ± 0.00 | 1.00 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 |
| Balancer | 0.88 ± 0.09 | 0.87 ± 0.10 | 1.00 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.00 | 0.99 ± 0.01 | 0.99 ± 0.01 |

![Table 3](image)

![Fig. 5](image)

Fig. 5 Muscle activity (sEMG envelopes) for each subject. Each column is referred to one of the four subjects (S1, S2, S3, S4). Rows 1–6: trapezius, deltoids, pectoralis, triceps, biceps and rectus muscles. On the last 7th row, there are the elbow angles. Red and blue lines represent right and left, respectively. Darker lines represent the first repetition and lighter lines the last. Green and yellow background indicate the time intervals where, respectively, the right and left muscles were active (based on the nOptim algorithm), when overlapped, left and right muscles activate together.
almost all muscles except the deltoids, which had comparable values between subjects, and the rectus, which, as mentioned before, had a lower MP than the other subjects.

In Table 6, we report the muscular left and right symmetries; the muscular activity had negligible lags: smaller than 20 ms between the left and right sides of the body. Overall, the triceps, the trapezius and the biceps muscle were characterized by high symmetry values, for S2, S3 and S4, but not for S1. The activation of pectoral muscle was highly symmetrical for S2, with lower but still reasonable symmetry values for the other subjects. The deltoid was highly symmetrical for S3 and S2. Finally, the rectum abdominis was characterized by high symmetry values for all subjects.

Discussion

This study was conducted to test an instrumented setup, protocol and set of parameters developed and selected to provide an objective and thorough evaluation of a gesture widely used both as training and as a discipline: the bench press. In the following, we will discuss (i) the usability and efficacy of the evaluation proposed for assessing the bench press gesture and (ii) the muscle and kinematic strategies adopted by the four elite athletes. In the latter case, we will also compare and examine the different muscle strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes. Due to the small number of subjects and heterogeneity of the athletes tested (different level of expertise and impairment), the results cannot be generalized. However, this work is a first proof of concept that the proposed instrumented evaluation allowed to discriminate the kinematic and muscular strategies adopted by the able-bodied athlete and the three impaired athletes.

Usability and efficacy of the instrumented evaluation for assessing the bench press gesture

As mentioned before, the main goal of the study was to test if the evaluation proposed was capable to effectively provide a complete and in-depth characterization of the bench press gesture regardless of the athletes’ level of ability and experience. To prove the usability and efficacy of the assessment, we conducted a series of case reports. We evaluated the bench press gesture of a heterogeneous group of athletes: an unimpaired athlete with a lower level of competition and three impaired athletes who, at the time, were members of the national bench press Paralympic team. The results obtained by the instrumented evaluation confirm the efficacy of the setup, protocol and parameters designed and selected in the study. Despite the different impairment and competition level of the athletes tested, with the instrumented evaluation, we were able to describe the level of performance of each athlete and recognize and unveil the muscular and kinematic strategies that
the athletes adopted to execute the gesture. The usability, efficacy and the efficiency of the instrumented evaluation proposed is also confirmed by the few studies published in literature [6–9, 19]. The assessment results, indeed, are not only consistent with the outcomes of these studies, but also provide relevant additional information regarding gesture performance, especially the muscle strategies adopted to execute the gesture. By adding muscles to the evaluation protocol (biceps, trapezius and rectus abdominis), we were able to discover specific compensatory muscle strategies not observed in previous studies [6, 9, 19]. In the following, will discuss these strategies in detail.

**Kinematic and muscle strategies: unimpaired and impaired athletes**

The qualitative and quantitative assessments of the kinematic data highlighted no kinematic differences between the three athletes with motor impairment: they performed the three bench press gestures with high symmetry and with low variability when repeating the gesture. The athlete without disability, who had less experience, had a lower level of repeatability and symmetry.

On the contrary, the analysis of the muscle activation profiles and a set of parameters, some of which were considered in previous studies [6, 9, 19], highlighted differences in the muscle strategies adopted to perform the gesture. Each athlete adopted an individual-specific muscle pattern.

We expected the biceps muscle to be responsible for the elbow flexion while the triceps for the elbow extension [20]. However, this behavior is visible only in the unimpaired athlete. Instead, all the athletes with motor impairments displayed an additional activation of the triceps between 10 and 30% of the movement, which is probably the result of a more controlled eccentric movement.

The normalized peak amplitude values of the pectoralis and the triceps were higher for the unimpaired athlete, except for the triceps of the amputee. This is in accordance with Ref. [6], where researchers found that the unimpaired athlete had higher activation peaks for those muscles when performing 1RM. In addition, the unimpaired participant had higher activation peaks for his biceps and trapezius, two muscles not considered in Ref. [6].

As previously mentioned, another muscle not investigated in previous studies is the rectus abdominis. This muscle was active during the entire movement for the able-bodied individual, while the disabled participants activated the rectus abdominis muscles only during the lift phase. This could be due to the different lying position. In fact, lying on the bench without lower limb support on the floor led to a higher body-barbell center of gravity, inducing impaired athletes to rely more on the stabilizer’s muscles to support the load without lateral imbalances [6]. From this, we can deduce that for the motor impaired athletes, the lack of support of the lower limbs, due to both their motor impairment and body-bench positioning, induced different muscle activation patterns.

Furthermore, differences between the unimpaired and impaired athletes were observed also in terms of left and right symmetry of the muscular activations. In Ref. [9], the authors evaluated the muscular symmetry during the bench press gesture only as the difference between left and right root mean square. Here, we measured differences in the modulation of amplitude between the two signals and their lag: the cross-correlation between the homologous muscle on the two sides of the body [21]. With these measures, we were able to detect a left–right asymmetry in the muscle activations of the able-bodied athlete. No differences in the left–right muscle activations were observed in the impaired athletes.

**Conclusions**

This study is the proof of concept that the proposed instrumented evaluation allows the identification, in both unimpaired and impaired athletes, of individual-specific muscle strategies, leading to similar kinematic performance while practicing the bench press exercise. With respect to previous work [6, 9, 19], this study investigated kinematic and muscle parameters, describing with quantitative measures, the different strategies adopted to compensate the individual motor impairments, even those that did not lead to a difference in kinematic performance. In addition, the present work extends the analysis of the muscle activity to six bilateral muscles, contributing to a more complete description of the strategy adopted by the subjects.

**Practical applications**

The methods and findings presented in this study could be useful for both coaches and athletes. The experimental setup and protocol that we have proposed to assess motor performance and muscles activity during the execution of bench press movements could indeed be applied to enhance training and to improve and optimize the athletic gesture. Kinematics allows verifying that performance improved and/or that the requirements for competitions are achieved, while muscle activations highlight the underlying different strategies. The latter point is important, especially in Paralympic sports, where athletes could have a different level and type of disability, thus reaching high, and even similar, levels of performance by adopting deeply different muscular strategies. Some of these strategies can increase the risk of injury in athletes [20], especially in presence of bilateral asymmetry, thus we monitored those aspects. Moreover, our findings and the approach proposed
within the study could be relevant for both sport performance and physiology research.

To date, little published literature has based its work on impaired athletes, despite the fact that the number of impaired people involved in sport disciplines is constantly growing since sports and physical activity improve quality of life and health [1], preserving residual motor function [21] and promoting social participation [2]. Moreover, since teams of athletes of Paralympic disciplines often have impairments that differ for their nature and have different impact on physical abilities, a characterization, as the one proposed in this work, involving subjects with different motor impairments, is important.

Furthermore, the methods and analysis proposed within the study could be applied to a multiple of sport disciplines by slightly adapting the setup accordingly to the gesture selected.

Limitations and future research

We acknowledge that the small data sample size and the heterogeneity of the population tested did not allow for a meaningful statistical comparison between groups. This is a case reports study, whose preliminary findings do not allow a generalization of the results but are a starting point for future research. We also admit the limitation introduced by the exclusive investigation of Paralympic bench athletes with a high level of experience, which have stable muscle patterns induced by high-level training and expertise.

Future research will focus (1) on larger groups of athletes with similar disabilities to fully validate the proposed evaluation protocol and (2) on the characterization of bench press movements executed by inexperienced athletes to assess the effect of experience and gender on movement performance and on the muscle strategies adopted.

Author contributions Conceptualization, ADL, AM, MCa, and MCo; methodology, all the authors; software, AB, ADL, GM, and MCa; formal analysis, AB, ADL, GM, and MCa; investigation, ADL, MCa, and MCo; writing—original draft preparation, AB, ADL, MCa, and GM; writing—review and editing, all the authors; supervision, ADL, MCo, and AM. All the authors have read and agreed to the published version of the manuscript.

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Data availability The data presented in this study are available on reasonable request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval All the procedures were approved by the local ethical review board (Comitato Etico Regione Liguria, protocol n. CER Liguria: 585/2021) and the participants gave informed consent in accordance with the ethical standards of the 2013 Declaration of Helsinki.

Informed consent statement Informed consent was obtained from all the participants involved in the study.

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