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Neuromuscular Excitation Pattern in Expert Indoor Skydivers

Susanna Rampichini [1], Eloisa Limonta [1,*], Irene Di Giulio [2], Marta Borrelli [1], Emiliano Cè [1], Giuseppe Coratella [1], Johnny Padulo [1], Stefano Longo [1] and Fabio Esposito [1]

[1] Department of Biomedical Sciences for Health, Università degli Studi di Milano, 20133 Milan, Italy; susanna.rampichini@unimi.it (S.R.); marta.borrelli@unimi.it (M.B.); emiliano.ce@unimi.it (E.C.); giuseppe.coratella@unimi.it (G.C.); johnny.padulo@unimi.it (J.P.); stefano.longo@unimi.it (S.L.); fabio.esposito@unimi.it (F.E.)

[2] Centre for Human and Applied Physiological Sciences, King's College London, London SE1 1UL, UK; irene.di_giulio@kcl.ac.uk

* Correspondence: eloisa.limonta@unimi.it; Tel.: +39-2-50314644

Featured Application: This study provides valuable insights into the specific muscle contributions required for adopting and maintaining various postures during indoor skydiving. These findings are essential for preventing joint and muscle overloading in novices and for preparing elite practitioners for competitive choreography. Furthermore, a novel index, termed NeLo, has been introduced to provide quantitative information about muscle excitation when several muscles are concurrently investigated. Such an index can be categorized into general, regional, and functional standpoints and holds potential for applications across several sport science fields where a quantitative contribution of various muscle groups to different tasks must be assessed.

Abstract: The evolution of indoor skydiving from military origins to a globally recreational pursuit has attracted individuals without prior specific training, exposing them to the heightened risk of muscle–joint injuries associated with indoor skydiving. This study aims to assess the muscular excitation patterns in highly skilled instructors to determine the optimal activation strategies for preventing musculoskeletal injuries. Nine expert indoor skydiving instructors (M/F: 8/1; age 31 ± 7 years; body mass: 70.5 ± 11.1 kg; stature: 1.74 ± 0.09 m) were enrolled. The surface electromyographic signal was recorded on the anterior deltoid, AD; posterior deltoid, PD; pectoralis major, PM; latissimus dorsi, LD; rectus abdominis, Rabd; erector spinae, ES; rectus femoris, RF; and biceps femoris, BF for each position: PRONE, SUPINE, SIT, and head-down (HD). A synchronous heart rate was recorded to assess the cardiac engagement. The neuromuscular load (NeLo), representative of the excitation amplitude of a muscle set, was determined for each position across different body regions. PRONE and SUPINE were the least demanding in terms of cardiac engagement (67 ± 6 and 85 ± 8 bpm, respectively) and exhibited the lowest neuromuscular excitation (24 ± 10 and 24 ± 8% Max, respectively). By contrast, HD exhibited the highest cardiac (127 + 18 bpm) and neuromuscular (71 + 11% Max) engagement and particularly in the lower-trunk and lower-limbs muscles. SIT predominantly engaged upper-trunk and shoulder muscles. The findings indicate the significant engagement of the musculature surrounding the shoulder joint and that responsible for lower-trunk stabilization in maintaining the investigated positions. A targeted training regimen on strengthening these muscles is advised before practicing indoor skydiving to prevent shoulder joint injuries or lower back muscle overloads.

Keywords: electromyography; muscle excitation; motor control; injuries; wind tunnel; aerospace medicine

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1. Introduction

Indoor skydiving has witnessed a substantial growth in popularity worldwide. It developed from a training venue, specifically dedicated to military paratroopers, into a facility with safe and stable environmental conditions suitable for training sessions and competitive events of the International Aeronautical Federation [1]. During indoor skydiving competitions, practitioners must execute, while floating, a combination of maneuvers to perform coded sequences along pre-determined invisible paths inside the vertical wind tunnel, encompassing twisting and rolling movements in all directions by assuming different body postures. The posture adopted by the skydiver inside the wind tunnel determines the body surface exposed to the airstream, playing a crucial role in the success of these maneuvers, the precision of the direction, and velocity of the movements. Indeed, inside the wind tunnel, the skydiver experiences three different forces: (i) gravity, (ii) the aerodynamic force, and (iii) the force exerted by muscles to counteract the drag force acting on the body. The area of the body surface exposed to the airstream influences the aerodynamic force acting on the skydiver [2]. A fully extended supine or prone position maximizes the body's surface area exposed to the airstream, leading to a rapid ascent. In contrast, reducing the skydiver body surface exposed to the airstream by assuming more compact postures facilitates descent. Although expanding the body surface facing the airstream to gain height is intuitive, its execution against the wind tunnel airstream is considerably demanding, especially from a muscular standpoint, and necessitates a coordinated activation of multiple muscle groups. Efforts sustained by indoor skydivers expose the musculoskeletal system to a heighten risk of muscle overloads and joint injuries, resulting in cervical and lumbar back pain and shoulder dislocation [3–7]. During wind tunnel training, confidence is built through mastering a series of progressively challenging poses, starting with the least difficult position, lying prone (belly-to-earth), advancing to supine (belly-to-ceiling), then sitting, and finally, assuming a reversed position with the head towards the floor. To counteract the airstream and control each body posture, including an arched pose, several joints (such as the glenohumeral, spinal column, and acetabulo-femoral) are subjected to significant mechanical loads. These may contribute to muscular overloading and the development of osteoarticular pain [5]. The level of experience of individual skydivers may likely influence the optimization of muscle groups activation, thereby reducing the occurrence of muscles overloads, injuries, and detrimental co-contractions. Only a few studies have explored skydiving features, primarily concerning the dynamic modeling of the human body during freefall, parachuting-related injuries, and balance control [2,3,8]. Despite the growing popularity of indoor skydiving, a comprehensive description of the muscles engaged while fluctuating inside the wind tunnel is still lacking. Considering the risks of muscular overloads and joint injuries associated with indoor skydiving [3–6], an investigation into muscle activation patterns in experienced practitioners may provide important insights into the optimal neuromuscular strategy for maintaining basic positions and preventing the occurrence of discipline-related injuries. Furthermore, a detailed definition of the optimal muscular activation strategy when used as a reference would enable the identification of detrimental activations in beginners, a growing population within this discipline.

Therefore, the aim of the present study was to describe the muscular engagement in experienced indoor skydivers while assuming the four fundamental postures. Furthermore, in view of providing a quantitative measure of the overall muscular engagement, this study introduces a novel index, the neuromuscular load (NeLo), summarizing the neuromuscular engagement of a set of muscles that can be categorized by body location (trunk, arms, and legs; muscles positioned at the front or the back side of the body). In the field of motion analysis, the activation pattern of several muscles is typically represented by the root mean

squared values of each muscle as a function of time. While this approach is beneficial for detailing the extent and timing of muscles engagement during a single activity, it becomes less informative when comparing multiple activities, as a muscle-by-muscle analysis does not offer a clear understanding of the overall muscular engagement. A comprehensive description of muscular excitation during the four fundamental indoor skydiving postures in experienced practitioners could offer insights into the optimal neuromuscular strategy to maintain the basic positions. Additionally, it could shed light on which muscle groups a training protocol should focus on in order to minimize the risk of muscles injuries and overloading.

2. Materials and Methods

2.1. Participants

Nine indoor skydiving instructors (8/1 M/F; age 31 ± 6 years; body mass 70.0 ± 10.5 kg; height 1.74 ± 0.08 m; coaching: 6–8 h/week) with at least four years of indoor skydiving experience participated in this observational study. Inclusion criteria required no history of upper-limb and lower back muscle pain or injury or neurological or cardiovascular disease in the previous 12 months. After having carefully read the written information and received comprehensive details about the study aim and protocol, each participant signed the informed consent. The study was performed accordingly with the latest version of the Declaration of Helsinki and approved by the local ethical committee of the Università degli Studi di Milano (#84/23) 17 July 2023.

2.2. Experimental Protocol

All measurements were performed in a vertical wind tunnel facility, which consisted of a 20-m-tall cylinder with a diameter of 5.2 m (Aero Gravity, Pero, Italy). The airstream speed ranged between 192 and 280 km·h^{-1}. A total of eight muscles were recorded while instructors were floating in the tunnel assuming the following four fundamental postures for five minutes in a random order: lying horizontally with the abdomen facing down (PRONE, Figure 1a) or up (SUPINE, Figure 1b), sitting upright (SIT, Figure 1c), and assuming an upside-down attitude (head down, HD, Figure 1d). A minimum recovery break of four minutes was included between each trial.



Figure 1. Pictures showing the fundamental postures. (**a**) PRONE; (**b**) SUPINE; (**c**) SIT; (**d**) head down (HD).

2.3. Testing Procedures and Equipment

Upon arrival at the facility, participants' body mass and height were measured, and a wearable cardiac sensor (Faros 180, Bittium, Oulu, Finland) was placed on the chest to continuously collect a 1-channel electrocardiogram (ECG, sampling rate: 500 Hz) and obtain the heart rate (HR) as an index of the cardiac engagement in maintaining the target postures. The cardiac engagement was assessed as a central index of the effort sustained by participants to maintain specific postures. To determine a HR value representative of the resting condition outside the tunnel, participants were asked to remain supine for 15 min while the ECG was recorded. The average HR of the last five minutes was calculated (REST OUT). After the rest ECG recording, the participant's skin was prepared for surface electromyography (sEMG) to reduce the impedance at the electrode–skin interface. The skin over the muscles under investigation was shaved, abraded by an abrasive skin gel (Nuprep, Weaver and Co., Aurora, CO, USA), and cleaned. The sEMG signals were recorded using Ag/AgCl electrodes (active area: 1 cm^2; ARBO Kendall, Covidien LLC, Mansfield, MA, USA) placed at a 20-mm interelectrode distance. The sEMG was recorded at a 1000 Hz sampling frequency using bipolar probes (Free-EMG, BTS Bioengineering, Garbagnate Milanese, Italy) on the following muscles on the dominant side: anterior deltoid (AD); posterior deltoid (PD); pectoralis major (PM); latissimus dorsi (LD); rectus abdominis (Rabd); erector spinae (ES); rectus femoris (RF); biceps femoris (BF). For each muscle, the sEMG electrodes (mod. H124SG, Kendall, Covidien LLC, Mansfield, MA, USA) were placed over the muscle belly following the recommendations given by Barbero and Coll [9]. Additionally, to ensure the appropriate sEMG placement, participants were instructed to contract the target muscle, while an expert operator visually verified the signal quality during the contraction. A portable inertial unit equipped with a triaxial gyroscope and accelerometer (G-WALK, BTS Bioengineering, Garbagnate Milanese, Italy) was placed on the participant's back, approximately on the spinous process of the fifth lumbar vertebra, to record the 3D body's orientation simultaneously with sEMG.

After their preparation, participants entered the vertical wind tunnel and assumed the designated postures (Figure 1). The postures' sequence was randomly assigned, with HD, being the most demanding, always performed as the last posture. Since an assessment of the cardiac engagement was determined simultaneously, all the positions except HD were maintained for five minutes each to allow the participant's HR to reach a steady value. The HD position was maintained by each participant for a variable time interval (45–220 s), depending on individual ability. A 4-min recovery time separated each trial, contingent upon the return of the HR to resting values.

2.4. Data Analysis

The HR was determined on a beat-by-beat basis from the ECG signal through a freeware software (EDF browser, v1.98, Free Software Foundation, Inc., Boston, MA, USA) and successively averaged over the last minute for each posture. The sEMG signal was bandpass-filtered (bandwidth: 10–400 Hz) by a zero-lag 4th-order Butterworth filter. sEMG signal amplitude was determined calculating the root mean squared (RMS) of each sEMG channel. The RMS was calculated over a 15-s epoch within the initial 60 s for each posture, provided that the gyroscope signal was stable. Each RMS value was normalized to the posture that created the largest RMS for the same muscle. This approach was applied for each muscle to each posture. Lastly, to produce an index representative of the overall neuromuscular excitation for each posture, the RMS values of all the muscles recorded were summed and divided by eight (the number of muscles under investigation). This resultant value was defined as the neuromuscular load (NeLo). In addition to the single NeLo value indicative of the overall neuromuscular excitation, additional NeLo sub-indices have been

developed to better represent excitations within distinct body regions. Therefore, regional NeLo values (NeLoR) were also obtained grouping muscles upon craniocaudal and upon dorsoventral body regions. For craniocaudal regions, muscles were grouped as follows: (i) upper-trunk: AD, PD, PM, and LD; (ii) lower-trunk: Rabd and ES; and (iii) lower-limbs: RF and BF. Dorsoventral NeLo were derived by considering the four muscles located in the front side ($NeLo_{FRONT}$: AD, PM, Rabd, and RF) and the four muscles located on the back side ($NeLo_{BACK}$: PD, LD, ES, and BF). For each region and side, a NeLo value was determined adding the RMS values of the muscles within that region and then dividing the total by the number of the muscles involved. All the sEMG analysis was performed by a custom-built code (Matlab R2023, MathWorks, Natick, MA, USA).

2.5. Statistical Analysis

The statistical analysis was performed using SPSS (v28.0.1.1, IBM SPSS Statistics, Chicago, IL, USA). The Shapiro–Wilk test was employed to assess the normality of the distribution. In the case of a normal distribution, a one-way repeated measures ANOVA (ANOVA-RM) was used to test differences among the four body postures for HR and NeLo. A two-way ANOVA-RM was run to determine the differences in regional NeLo due to the two factors "posture" and "region". A similar statistical analysis was performed to examine differences between the two factors "posture" and "muscle". A Bonferroni correction was employed for the post hoc analysis. Friedman tests were applied in the case of non-normal distributions. Wherever significant differences were identified, to describe the magnitude of change, partial eta square (η_p^2) was used for the ANOVA-RM analysis, whereas Hedge's g was used for the pairwise comparisons [10,11]. η_p^2 values were classified as small if $\leq$0.06, medium between 0.06 and 0.14, and large if $\geq$0.14 [10]. Hedge's g values were classified as trivial for values $\leq$0.19, small between 0.2 and 0.6, moderate between 0.6 and 1.2, large between 1.2 and 2.0, and very large $\geq$2.0 [12]. Lastly, a cross-correlation analysis, determining a Pearson product moment, explored co-contractions among the investigated muscles. Very high correlation magnitudes (>0.71) were considered as co-contractions [12]. The level of significance was set at $\alpha = 0.05$. All data are expressed as the mean $\pm$ standard deviation (SD).

3. Results

3.1. Heart Rate

One-way ANOVA-RM showed large significant differences in HR collected in different postures ($F = 38.87$, $\eta_p^2 = 0.83$; Figure 2). All values assessed inside the wind tunnel were higher than REST OUT, evaluated outside the tunnel (PRONE: +21 bpm, $p = 0.009$, $g = 1.53$, $CI_{95\%}$= 0.63–2.73; SUPINE: +21 bpm, $p < 0.001$, $g = 2.47$, $CI_{95\%}$ = 1.13–3.78; SIT: +37 bpm, $p = 0.006$, $g = 1.63$, $CI_{95\%}$ = 0.64–2.60; HD: +59 bpm, $p < 0.001$, $g = 3.97$, and $CI_{95\%}$ = 1.97–5.96; Figure 2). HD elicited significantly higher HR values compared to PRONE (about 45%; $p < 0.001$; $g = 2.23$; $CI_{95\%}$ = 0.99–3.44; Figure 2) and SUPINE (about 43%; $p < 0.001$; $g = 2.62$; $CI_{95\%}$ = 1.22–4.00; Figure 2).

3.2. Neuromuscular Load Indices

A large posture effect was found in NeLo ($F = 37.42$; $\eta_p^2 = 0.82$; Figure 3a). Indeed, SIT and HD exhibited significantly higher values compared to both PRONE ($p = 0.003$, $g = 1.73$, and $CI_{95\%}$ = 0.69–2.73 and $p < 0.001$, $g = 2.27$, and $CI_{95\%}$ = 1.01–3.49 for SIT and HD, respectively; Figure 3a) and SUPINE ($p = 0.003$, $g = 1.72$, and $CI_{95\%}$ = 0.69–2.71 and $p < 0.001$, $g = 4.57$, and $CI_{95\%}$ = 2.30–6.84 for SIT and HD, respectively; Figure 3a). No significant difference was found in NeLo between PRONE and SUPINE and between SIT and HD.

The two-way ANOVA-RM did not find any interaction between posture and region. For clarity, the muscle groupings used to examine the regional differences in NeloR are as follows: (i) upper-trunk: AD, PD, PM, and LD; (ii) lower-trunk: Rabd and ES; and (iii) lower-limbs: RF and BF. The statistical analysis disclosed a large posture effect on regional muscle excitation ($F = 49.13$; $\eta_p^2 = 0.86$; Figure 3b). Indeed, compared to PRONE, the upper-trunk region showed significantly higher NeLo values during SIT ($p = 0.01$, $g = 1.64$, and $CI_{95\%} = 0.60–2.65$; Figure 3b) and HD ($p = 0.01$, $g = 1.4$, and $CI_{95\%} = 0.49–2.28$; Figure 3b). Higher values were also found in SIT and HD compared to SUPINE ($p = 0.03$, $g = 1.18$, and $CI_{95\%} = 0.35–1.99$ and $p < 0.001$, $g = 2.35$, and $CI_{95\%} = 1.06–3.61$ for SIT and HD, respectively; Figure 3b). The lower-trunk region exhibited significantly higher NeLo values during SIT compared to SUPINE ($p < 0.001$, $g = 2.34$, and $CI_{95\%} = 1.06–3.6$; Figure 3b) and during HD compared to PRONE ($p = 0.008$, $g = 1.45$, and $CI_{95\%} = 0.52–2.34$; Figure 3b); SUPINE ($p < 0.001$, $g = 2.56$, and $CI_{95\%} = 1.19–3.92$; Figure 3b); and SIT ($p = 0.013$, $g = 1.33$, and $CI_{95\%} = 0.44–2.18$; Figure 3b). NeLo of the lower-limbs region exhibited higher values in only HD compared to PRONE ($p = 0.004$, $g = 1.62$, and $CI_{95\%} = 0.63–2.58$; Figure 3b) and SUPINE ($p = 0.004$, $g = 1.62$, and $CI_{95\%} = 0.63–2.59$; Figure 3b). SIT appeared to show higher values, albeit not significant ($p = 0.064$). No significant differences were found for the regions within the postures.

Posture effects were also found by the two-way ANOVA-RM that evaluated the impact of posture and muscle position on the neuromuscular load values grouped according to muscular location (front vs. back side muscles). As mentioned earlier, $NeLo_{FRONT}$ included muscles located on the anterior side (AD, PM, Rabd, and RF), while $NeLo_{BACK}$ values were determined by muscles located on the posterior side (PD, LD, ES, and BF). No interactions were found between posture and position ($F = 2.01$; $p = 0.140$; $\eta_p^2 = 0.20$; Figure 3c). A large posture effect was found for muscular electrical activity in both anterior and posterior muscles ($F = 37.42$; $p < 0.001$; $\eta_p^2 = 0.82$; Figure 3c). Specifically, $NeLo_{FRONT}$ values doubled during SIT compared to PRONE ($p = 0.003$, $g = 1.66$, and $CI_{95\%} = 0.65–2.64$; Figure 3c) and SUPINE ($p = 0.003$, $g = 1.69$, and $CI_{95\%} = 0.67–2.68$; Figure 3c). During HD, $NeLo_{FRONT}$ exhibited a more pronounced increase, reaching threefold higher levels compared to both PRONE ($p = 0.011$, $g = 1.37$, and $CI_{95\%} = 0.47–2.24$; Figure 3c) and SUPINE values ($p = 0.004$, $g = 1.62$, and $CI_{95\%} = 0.63–2.58$; Figure 3c). In regard to $NeLo_{BACK}$ values, SIT differed only from SUPINE values (about +31%MAX, $p = 0.009$, $g = 1.43$, and $CI_{95\%} = 0.51–2.32$; Figure 3c), whereas HD exhibited significantly higher values compared to both PRONE (about +54%MAX, $p = 0.008$, $g = 1.44$, and $CI_{95\%} = 0.51–2.33$; Figure 3c) and SUPINE (about +58%MAX, $p < 0.001$, $g = 3.04$, and $CI_{95\%} = 1.46–4.60$; Figure 3c). No differences were observed in the $NeLo_{BACK}$ values between SIT and HD.

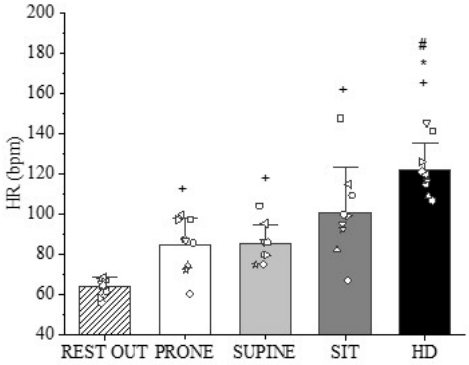


Figure 2. HR values determined in the resting conditions outside the tunnel and, for each posture, inside the tunnel. Dashed, white, light grey, dark grey, and black bars refer to the REST OUT, PRONE, SUPINE, SIT, and HD conditions, respectively. + $p < 0.05$ vs. REST OUT, * $p < 0.05$ vs. PRONE, and # $p < 0.05$ vs. SUPINE. HR values are expressed as the mean + SD.

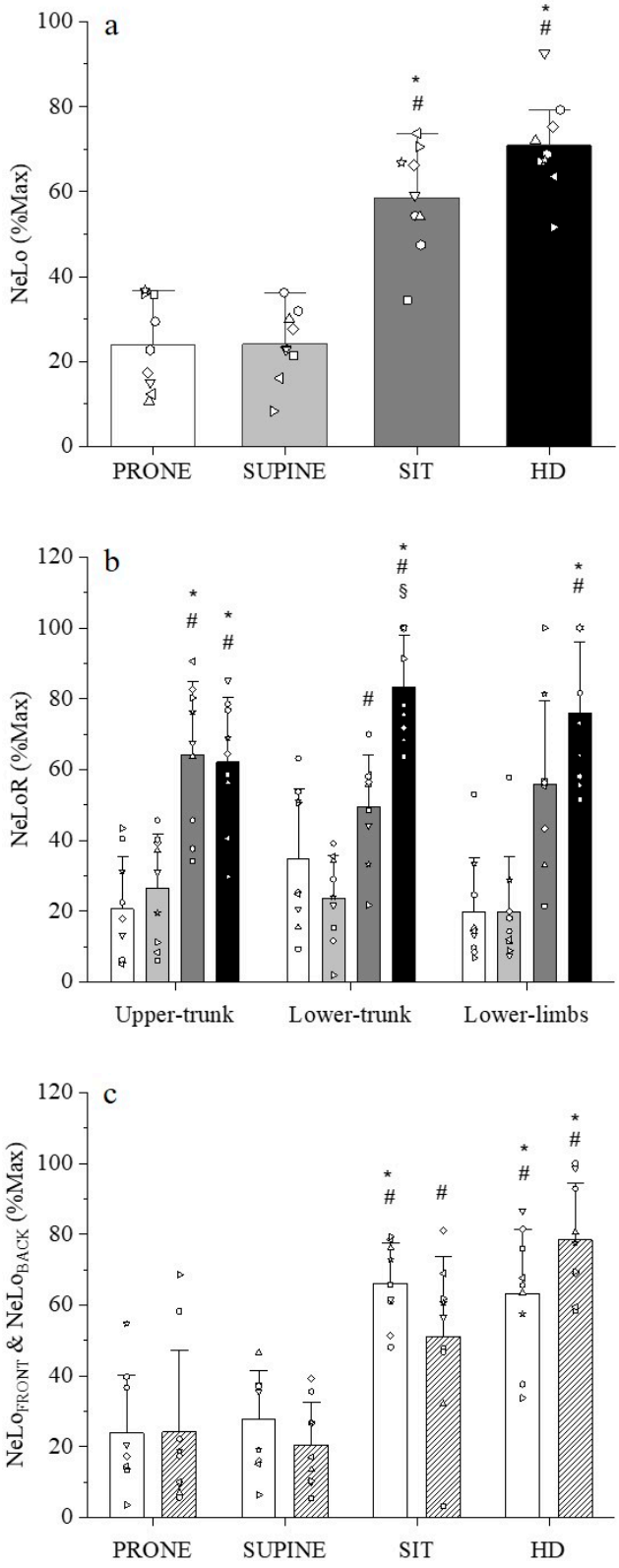


Figure 3. Mean values of NeLo (**a**) and regional NeLo (NeLoR (**b**)), along with $NeLo_{FRONT}$ and $NeLo_{BACK}$ (**c**), for each posture. White, light grey, dark grey, and black bars refer to the PRONE, SUPINE, SIT, and HD conditions, respectively. White and dashed bars refer to $NeLo_{FRONT}$ and $NeLo_{BACK}$, respectively. * $p < 0.05$ vs. PRONE, # $p < 0.05$ vs. SUPINE, and § $p < 0.05$ vs. SIT. NeLo values are expressed as the mean + SD.

3.3. Muscle Excitation

Figure 4 shows the mean RMS values determined for all the investigated muscles in each posture. Overall, PRONE exhibited a similar, modest excitation (below 30% of maximum) in all the investigated muscles, except for Rabd, which showed the highest excitation (close to 50% of the maximum; Figure 4a). During SUPINE, the highest excitation was observed in AD (approximately 48% maximum) and PD (about 33% maximum), whilst the remaining muscles were excited less than 30% of the maximum (Figure 4b). SIT was linked to increased excitation in almost all the investigated muscles, particularly those belonging to the upper-trunk region, while LD and BF exhibited the lowest contribution (about 30% and 38% of the maximum, respectively; Figure 4c). Finally, HD (Figure 4d) required a further increase in excitation of all the muscles under examination, particularly those belonging to the lower-trunk and lower-limbs regions.

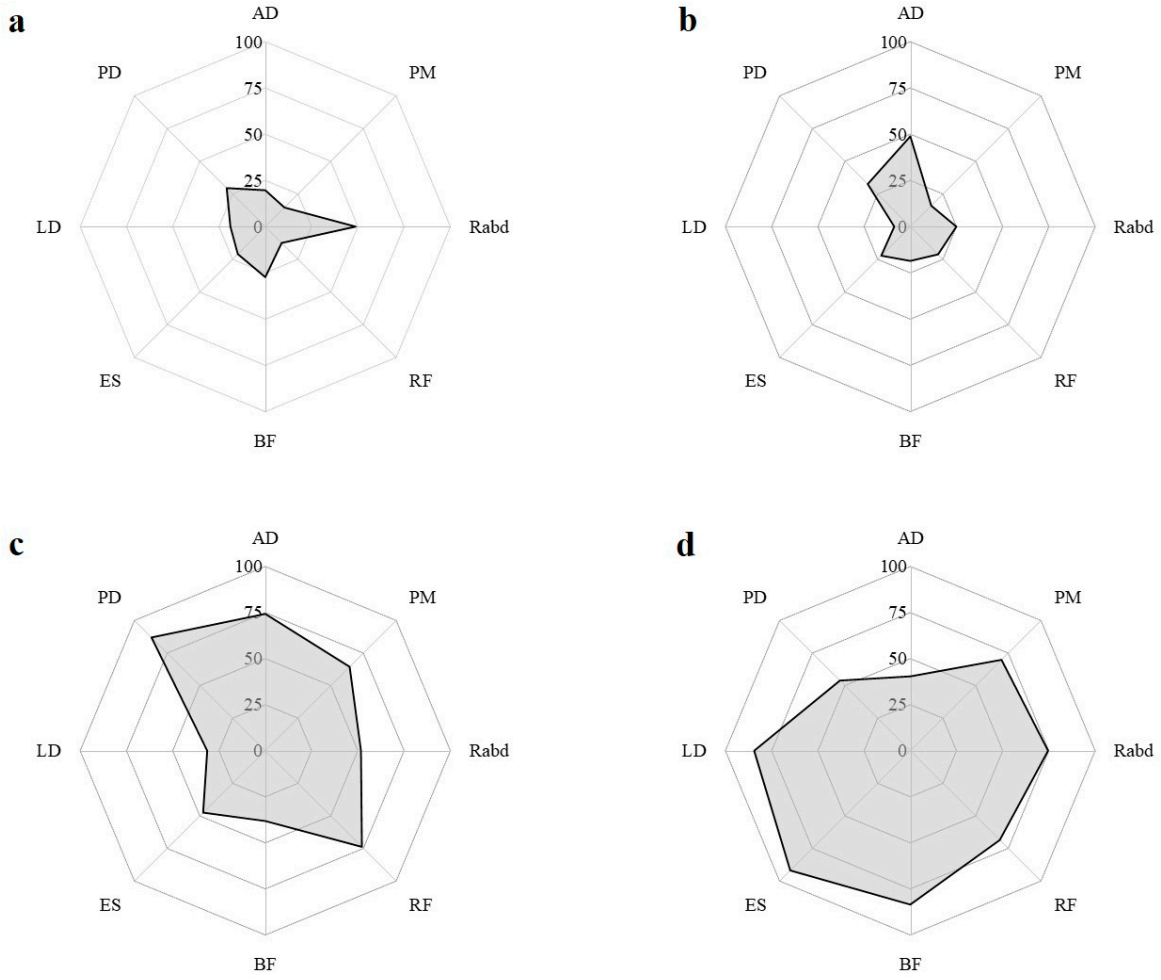


Figure 4. Average RMS values, expressed as the percentage of the maximal excitation of the investigated muscles for each posture. PRONE, SUPINE, SIT, and HD are shown in (**a**), (**b**), (**c**), and (**d**), respectively.

Table 1 shows the Pearson product moment correlations determined in PRONE, the only posture exhibiting significant co-contractions. Specifically, the correlation analysis revealed co-contractions between AD and PM (r = 0.83; p = 0.006; $CI_{95\%}$ = 0.32–0.96) and between LD and ES (r = 0.88; p = 0.002; $CI_{95\%}$ = 0.48–0.97).

Table 1. Pearson product moment correlations determined in PRONE. Bold numbers indicate a significative positive correlation. Anterior deltoid (AD), posterior deltoid (PD), pectoralis major (PM), latissimus dorsi (LD), rectus abdominis (Rabd), erector spinae (ES), rectus femoris (RF), and biceps femoris (BF). The significance level was denoted as * $p < 0.05$.

		AD	PD	PM	LD	Rabd	ES	RF	BF
AD	r		−0.025	**0.828**	−0.220	0.437	−0.291	−0.385	0.417
	p		0.949	*** 0.006**	0.569	0.239	0.448	0.306	0.264
	N		9	**9**	9	9	9	9	9
PD	r			−0.267	0.592	−0.321	0.377	−0.452	0.546
	p			0.487	0.093	0.400	0.318	0.222	0.129
	N			9	9	9	9	9	9
PM	r				−0.414	0.625	−0.458	0.116	0.349
	p				0.268	0.072	0.215	0.767	0.358
	N				9	9	9	9	9
LD	r					−0.593	**0.880**	−0.481	0.009
	p					0.092	*** 0.002**	0.190	0.982
	N					9	**9**	9	9
Rabd	r						−0.411	0.555	−0.076
	p						0.272	0.121	0.846
	N						9	9	9
ES	r							−0.319	−0.379
	p							0.402	0.314
	N							9	9
RF	r								−0.289
	p								0.451
	N								9

4. Discussion

This is the first study assessing neuromuscular excitation during indoor static skydiving in expert individuals. Muscle excitation was investigated in eight muscles while participants were maintaining the four basic skydiving postures. Moreover, we calculated a novel index representative of the neuromuscular engagement. The findings of the present study indicate HD as the most neuromuscular demanding posture, eliciting the highest engagement of all investigated muscles, particularly those of the trunk and lower limbs. Conversely, SIT recruited mainly trunk and shoulder muscles. PRONE and SUPINE exhibited the lowest neuromuscular excitation in almost all the examined regions, except for AD, which showed higher muscular electrical activation during SUPINE.

4.1. Preliminary Considerations on the HR Response

Compared to the resting value determined in the supine position outside the wind tunnel (REST OUT), HR exhibited a marked rise across all the postures within the tunnel. This finding is coherent with the cardiac acceleration related to different postures and any increase in physical activity [13,14]. Indeed, postural changes might be accompanied by a reduction in blood venous return to the heart chambers due to the gravitational effect (blood pooling). The consequent drop in arterial blood pressure evokes a positive chronotropic effect driven by a withdrawal of the parasympathetic branch and a rise in sympathetic arm activity. Nonetheless, a positive chronotropic effect occurs to increase the cardiac output and meet the rising metabolic demands of the exercising muscles when the level of physical activity increases [13,14]. It is to be noted that the higher HR value observed in the supine position inside compared to outside the tunnel cannot be attributed to postural

adjustments. Rather, it likely indicates a sympathetic activation, aimed at meeting the higher energy demand required by the postural muscles involved in the maintenance of the target posture [14]. When comparing the different postures inside the tunnel, the impact of the gravitational effects and of the changes in neuromuscular activation on the HR response are expected to exert distinct influences, depending on which posture is adopted. Specifically, the heightened neuromuscular activation required to maintain the posture against the airstream is expected to have a positive chronotropic impact in both SIT and HD. Conversely, the impact of gravity on the heart pump is supposed to yield opposite effects between SIT and HD. In SIT, a rise in HR is expected to address the reduced venous return due to lower limbs blood pooling. Conversely, the reversed position in HD would increase the blood pressure on baroreceptors located in the aortic arc and carotids; this would likely evoke a baroreflex negative feedback, an increase in vagal activity and a sympathetic withdrawal, thus decreasing the HR [15–17]. The lack of differences between the HR determined in HD and SIT, in our study, indicates a predominant role of the neuromuscular activation over the baroreflex negative feedback. Collectively, these findings suggest that any gravitational-induced inhibition of sympathetic activity and any baroreflex-related adjustments are effectively counterbalanced by the heightened sympathetic activation required to meet the energy demand of the target task.

4.2. Neuromuscular Activation

As this is the first study exploring the neuromuscular excitation during indoor static skydiving, any comparison with previous data is not possible. A description of the neuromuscular excitation will be discussed from distinct standpoints, encompassing the anatomical region to which the muscle belongs, an in-depth analysis of the principal muscles engaged for the different postures, and co-excitations detected through the cross-correlation analysis. The NeLo index, newly proposed in the present study, is intended to complement traditional metrics of neuromuscular excitation. Typically, neuromuscular excitation is assessed using various frequency and time domain indices [18,19], such RMS. For tasks involving several muscles, this approach generates a number of RMS values equal to the number of muscles under investigation, providing a detailed description of each single muscle excitation. However, such an approach does not offer a measure of overall excitation, which represents fundamental information for coaches and athletes in a discipline characterized by the excitation of synergistic muscles during demanding static tasks, like climbing or gymnastic rings. The development of an index indicative of overall excitation, such NeLo, allows coaches and athletes to optimize training procedures by focusing on a specific group of muscles. In this context, NeLo identified SUPINE and PRONE as the least demanding postures, not only from a cardiac perspective but also from a neuromuscular standpoint (Figure 3a). These two lying postures were shown to be equally relaxing. Indeed, the comparison between NeLo values obtained during SUPINE and PRONE did not show significant differences in overall excitation. The absence of significant differences was also observed when the contribution of muscles of different craniocaudal anatomical regions was compared (Figure 3b), nor when muscles have been merged in the transverse plane (front and back side of the body; Figure 3c). This latter finding was unexpected. While in the SUPINE posture, the skydivers adopt a relaxed position leaning against the airstream with their back; in PRONE, they have to face the wind, assuming an arched position with backward extension. Considering that, outside the tunnel, this position necessitates the activation of back extensors muscles [20], the absence of a higher excitation in the back muscles while assuming the arched position suggests a compensatory mechanism that, inside the tunnel, can be attributed to the airstream pressure exerted by the aerodynamic force acting on the body surface. Consequently, the muscular effort

sustained by the skydiver in PRONE appears comparable to the SUPINE posture, likely aiming at modulating muscular excitation solely for minor adjustments. Such a scenario seems plausible particularly among expert skydivers, like the instructors recruited for the present study. Indeed, these two postures are usually introduced to beginners at different stages, with PRONE being presented first due to its lower difficulty. For beginners, the assessment of muscular excitation in these two postures is likely to reveal differences that may be attributed to detrimental co-contractions that are physiological when performing unfamiliar tasks. Differently for professional skydivers, these postures showed to be equivalent in terms of muscle engagement. This suggests that expert skydivers are able to modulate the neuromuscular control to minimize the effort even during tasks of different difficulties. Similar neuromuscular adaptation was also reported in other sports wherein a high level of specialization is reached in response to long-term training, resulting in a lower level of muscle activity [21].

NeLo increased considerably in the other two investigated conditions, SIT and HD, resulting in the most challenging postures. One possible explanation of this observation may be attributed to the different body surfaces exposed to the airstream compared to the lying postures. In PRONE and SUPINE, the skydiver faces the aerodynamic force with a wide, uniform, and solid surface that, in laid postures, constitutes predominantly the trunk in the frontal axis. Conversely, during SIT and HD, the surface exposed to the airstream is characterized by a combination of several unsteady and scattered surfaces defined by the projection of the limbs in the anatomical frontal axis and the projection of the head, shoulders, and trunk in the transversal axis. Moreover, it has to be considered that, in PRONE and SUPINE, the surface exposed to the airstream presents limited degrees of freedom due to the reduced mobility of the spine [22]. In contrast, in SIT and HD, the surface upon which the airstream pressure acts, is made of several small-surface segments, each characterized by elevated degrees of freedom [2]. In this condition, a relaxed position is not possible, and the stabilization of the different surfaces can be ensured only by activating all the muscles surrounding the joints that master these body segments. Interestingly, the muscles of the front side appeared to contribute equally to the muscles in the back side in all the investigated postures, adapting their excitation level uniformly, possibly to stabilize the different body districts. A significant co-contraction was observed in PRONE between AD and PM, which is likely to stabilize the joint against the airstream and between LD and ES (Table 1) to facilitate the arched position and stiffen the abdomen wall in all directions. This latter outcome is in line to that reported by McGill et al. which, in their study, discussed some issues inherent to the role of back muscles in trunk stabilization [23]. Going more into detail on muscular excitation across the different postures, the present study delineates two opposite scenarios. The first one, adopted to maintain the two lying positions, is characterized by the lowest muscular excitation, wherein nearly all muscles activate less than 30% of their maximal excitation. During PRONE, only Rabd muscle excitation reached 50% of the maximum, likely to stiffen the abdomen wall. During SUPINE, the highest excitation was observed in AD and PD. This activation can be explained by the need to stabilize the shoulder joint [24]. The other scenario occurred during the two upright postures and is characterized by an enhancement of the excitation of all the investigated muscles. Most muscles were excited to more than 50% of the maximum observed across the different postures. Specifically, during SIT, the highest excitations were observed in the anterior muscles and in PD. Conversely, among the muscles positioned posteriorly, the greatest muscle electrical activity was found in PD and ES, likely to stabilize the trunk and the shoulders. In this posture, indeed, the high range of motion of the shoulder joints needs to be actively limited to counteract the action the airstream imposes on the upper limbs. A previous study attributed a role to the posterior deltoid in preventing

luxation of the humeral head and to the anterior deltoid in preventing anterior humeral joint luxation and stabilizing the glenohumeral joint [25]. This suggests that, during indoor skydiving, the anterior and posterior deltoid, in synergy with the rotator cuff muscles, play a substantial role in maintaining shoulder joint stability. Interestingly, the maximum excitation of PM has been observed during this posture. Such finding suggests a double function for PM: (i) to provide a substantial contribution in aiding AD and PD in the stabilization of the shoulder joint and (ii) to acquire more lift by pressing on the airstream with the shoulder, upper back, and head. Concerning the lower regions, the low excitation of LD was unexpected, given that this muscle plays a pivotal role in extending the back while assuming a seated position [26]. Differently, ES and Rabd showed notable excitation, with the former enhancing the lumbar lordosis to achieve the appropriate attitude of the trunk for this specific posture and the latter promoting core stabilization. Regarding the lower limbs, RF actively supported hip flexion with a scarce contribution of the antagonist in the stabilization of the lower limb [26]. During HD, as anticipated, all investigated muscles exhibited a considerable heightened engagement. LD and ES showed the highest enhancement, indicating the critical role of stabilizing the thoracolumbar region, likely to counteract the airstream propensity to turn the participant's body upside down when the skydiver is assuming the reversed position. Moreover, a noteworthy simultaneous activation of RF and BF has been observed, indicating a synergistic action of these muscles in stabilizing the lower limbs against the pressure the aerodynamic force exerted on the lower limbs. Furthermore, it cannot be excluded that the coactivation of RF and BF is aimed at balancing the effort exerted by the arms and trunk against the airstream.

The findings of the present study offer insights into the specific muscle contributions required for adopting and maintaining various postures, crucial for indoor skydiving coaches and expert skydivers preparing for choreography in competitions. Moreover, the findings of this study may have important implications for beginners and intermediate fliers. Indeed, mapping the primary muscles used by expert instructors to maintain specific postures could serve as a practical guidance for novices to target the correct muscle activation during training. For example, this study revealed the need for beginners to strengthen the muscles surrounding the shoulder and those stabilizing the lower trunk to effectively manage the first stages of indoor skydiving, where practitioners are asked to master the PRONE position and, subsequently, the SUPINE position. Practical indications can be found for intermediate practitioners, as well. Indeed, once skydivers have become proficient in PRONE and SUPINE and move on to mastering the SIT position, this study, in addition to the shoulder and lower back muscles, recommends including RF in the strengthening program to enhance the lower limb control. Lastly, the outcomes of the current study provide valuable indication to expert skydivers. Indeed, they are advised to focus on strengthening the lower trunk and lower limb muscles to ensure core stability and enhance lower limb control when the HD position has to be maintained. It is plausible that the proper activation of only the relevant muscles will result in a more efficient performance that, in turn, should reduce the onset of fatigue and the risk of muscle–joint overload and injuries. Future studies evaluating the occurrence of muscle–joint injuries in indoor skydiving practitioners with different expertise are advisable to verify the existence of a correlation between a specific neuromuscular activation pattern and injury risk. Nonetheless, future studies on neuromuscular activation in the expert and less skilled groups (beginners, recreational, and intermediate practitioners) could disclose different excitation strategies. Such insights would be valuable to monitor skill progression and retention and adjust pitfalls in a trainee's technique. Another aspect that deserves to be investigated is the application of conventional [27,28] and novel analysis [29,30] of sEMG to detect fatigue onset during indoor skydiving.

This study presents the following limitations. A surface EMG signal was acquired in a single differential configuration employing bipolar probes. This configuration presents several limitations related to interelectrode distance, conduction volume dimension, muscle length, contraction mode, and electrodes positioning, all of which may impact on the information embedded in the signal [31]. High-density EMG configuration, augmenting the number of recording sites and thus enhancing the spatial resolution, might have mitigated some of these limitations. Although this advanced technology would have been preferable for exploring muscular excitation, the experimental conditions required wireless technology that, in the form of high-density EMG, was not available at the time of the study. Nonetheless, it is worth noting that, in the current study, the level of muscular activity was compared within the same detection site across different postures, with the electrodes remaining in place throughout the entire experimental session. This ensured that any confounding factor associated with electrodes repositioning was avoided. Moreover, since the findings of this study derived from a within-subjects analysis, it is reasonable to assume that any limitations inherent to this type of detection affected the signal obtained for each posture equally. Another limitation relates to the maximum voluntary contractions that were not associated with a load cell signal; therefore, it was not possible to quantify the force expressed by each muscle during the maximum activation. Lastly, the study's sample size was limited. This limit arose from the need to determine the optimal neuromuscular excitation during indoor skydiving, which could only be assessed in expert practitioners. In the field of indoor skydiving, only a restricted population has developed the skills to optimally control their body during flight, thereby limiting the number of eligible participants. Moreover, it is important to note that the aim of this study required the involvement of a restricted population of expert skydivers; therefore, the findings cannot be generalized to other populations. However, given that this study aims to establish a reference for optimal muscle activation in maintaining the four fundamental postures during in indoor skydiving, future studies involving a broader population of expert practitioners is advisable to strengthen the findings.

5. Conclusions

This first study on neuromuscular activation during indoor static skydiving reveals the occurrence of two main scenarios observed among expert indoor skydiving instructors when assuming the four basic postures. The two lying poses exhibited the lowest neuromuscular load, whereas the reversed position (HD) appeared as the most demanding posture from both a cardiac and neuromuscular perspective. In the PRONE and SUPINE positions, the primary muscles involved in posture maintenance were those surrounding the shoulder (AD and PD) and the lower trunk (Rabd and ES), likely for stabilization purposes. During SIT, muscles showing the highest contribution were AD, PD, and PM, likely stabilizing the shoulder joint, and ES and RF to adopt an arched attitude and control the lower limbs. During HD, the posterior muscles play a pivotal role in maintaining the position with LD and ES engaged for trunk stabilization and RF and BF to control the attitude of the lower limbs.

Notably, in the present study, a new index (NeLo) has been introduced to provide quantitative information about muscle excitation when several muscles are concurrently investigated. Differently from conventional time and frequency domain indices, which offer insights on individual muscles, NeLo extends the comprehension on muscle excitations to a broader perspective. For example, in the study by Irwin et al., which examined changes in the excitation of various muscles across repeated gymnastic ring routines [32], a NeLo index based on muscles grouped by their roles might have offered a functional perspective on the decrease in muscle excitation exhibited by the different investigated muscles. Additionally,

this index can be easily adapted to various subsets, such as general, regional, and functional standpoints, according to the specific needs of the investigators. Given its versatility, NeLo holds significant potential for applications across several sport science fields where a quantitative contribution of various muscle groups to different tasks must be assessed. NeLo could also offer valuable insights in a rehabilitation context evaluating patients' residual muscle excitation capacity and monitoring the effectiveness of an intervention. Notably, since NeLo offers an overall perspective of neuromuscular excitation, it prevents determining the contribution of individual muscles unless there are further computations. Lastly, NeLo may give valuable information, provided that EMG signals from multiple muscles are acquired. This data collection, however, requires devices equipped with several probes in a wireless configuration, a sort of technology that might be relatively expensive. Future studies involving practitioners with different levels of expertise might offer valuable insights into the strategies currently adopted when approaching the fundamental postures as beginners. Such information may represent a crucial starting point for injury prevention.

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