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A Diagonal Movement Pattern of Arm Elevation and Depression in Overhead Throwing Athletes: An Exploratory Kinematic Analysis for Clinical Application

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Abstract: Assessing scapular position and motion during functional arm movement patterns may add relevant information to the evaluation of the clinical status and athletic performance of overhead sports athletes' shoulders. This study aimed to examine the three-dimensional scapular kinematics of elite volleyball players with (n = 11) and without scapular dyskinesis (n = 11) in comparison to non-athletes (n = 27). Four distinct arm elevation/depression tasks were assessed: shoulder abduction/adduction, flexion/extension, scaption, and a diagonal movement pattern mimicking throwing (proprioceptive neuromuscular facilitation diagonal 2 for flexion/extension or PNF–D2–flx/ext). Kinematic data was recorded from the spiking/dominant shoulder using an electromagnetic system (FASTRAK, Polhemus Inc., Colchester, VT, USA); MotionMonitor v9 software, Innovative Sports Training, Inc., Chicago, IL, USA). The study compared scapular rotations at 15° intervals of humero-thoracic (HT) angles, ranging from minimum to 120°. Significantly different 3D scapular kinematics were observed between traditional arm motion tasks and PNF–D2 arm motion task (HT angle × task interaction effect, $p < 0.001$, $0.275 \leq \eta_p^2 \leq 0.772$). However, when considering the combined influence of phase, HT angle, task, and group factors, no differences were found between groups (phase × HT angle × task × group, $p \geq 0.161$, $0.032 \leq \eta_p^2 \leq 0.058$). The inclusion of a functional arm movement pattern when evaluating scapular position and movement in overhead athletes does not appear to be mandatory. However, these findings are preliminary and highlight the need for more research in this area.

Keywords: dyskinesis; overhead sports; rehabilitation; scapula

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1. Introduction

Assessing scapular position and motion is paramount in the evaluation of the clinical status and athletic performance of overhead sports athletes' shoulder function [1,2]. Most often, the resting arms position combined with arm elevation and depression in the sagittal (flexion/extension), frontal (abduction/adduction) and scapular ("scaption") planes are used as movement performance tasks [2,3]; however, it is arguable that constraining shoulder movement to the abovementioned specific planes of motion may be sufficient to compare and generalize scapular kinematics for functional humeral movements such as during work tasks or activities of daily living [4–9], and, eventually, for an overhead throw, spike or serve (henceforth collectively termed as "throwing" for simplicity purposes, unless otherwise stated).

The unilateral overhead throwing motion involves considerable amounts of shoulder external (late coking)/internal (follow-through) rotation to generate adequate angular momentum, most often to accelerate a ball (and decelerate the arm) [10,11]. Scapula and humerus movements are multiplanar (3-dimensional [3D]), coupled and coordinated during arm elevation [12], and hence believed to be equally so during overhead throwing. Evaluations of 3D scapular kinematics in overhead throwers have thus evolved from simple humeral positioning in the frontal, sagittal, or scapular planes to humeral motion in the horizontal plane (shoulder internal/external rotation) with the arm at 90° of abduction [13,14] and, ultimately, simulation of a throwing action [15–18]. In an overhead throw, the scapula appears to externally rotate, upwardly rotate, and posteriorly tilt during the early cocking phase of the cycle, progresses into internal rotation after maximum humeral horizontal abduction and reaches the highest posterior tilting at the late cocking phase (maximum humeral external rotation). During the arm acceleration phase, the scapula seems to move toward greater internal rotation and begin to anteriorly tilt. At maximum humeral internal rotation, the scapula ends in internal rotation, upward rotation, and anterior tilting [15–18].

During the rehabilitation continuum, the training of movement patterns emphasizing functional and specific sports gestures are considered valuable to improve performance before returning to sports [19]. Diagonal humeral movement pattern training, combining shoulder flexion with horizontal abduction and external rotation and shoulder extension with horizontal adduction and internal rotation, are commonly used, as they mimic the throwing motion [20]. These movement patterns increase cortical recruitment of sensorimotor areas [21], activate key shoulder muscles, such as the serratus anterior, anterior deltoid, infraspinatus, upper, middle, and lower trapezius, as well as muscles involved in the kinetic chain of the throwing motion, such as the erector spinae [22], and improve functional performance [20], offering a superior rehabilitative value than simpler humeral movements, such as shoulder flexion [21] or shoulder scaption [22]. To date, however, how the scapula moves during the diagonal humeral movement patterns described above, also known as diagonal 2 pattern for flexion (PNF–D2–flx) and diagonal 2 pattern for extension (PNF–D2–ext) of proprioceptive neuromuscular facilitation concept, respectively, has not been explained. Evaluations, exercises, and manual interventions may be better designed and delivered if such knowledge were available to healthcare and sports professionals and researchers.

The primary objective of this study was to provide a comprehensive description of scapular orientation during the PNF–D2–flx/ext task. Additionally, we aimed to compare the scapular orientation during this PNF task with that observed in three traditional constrained arm motion tasks, namely shoulder abduction/adduction, flexion/extension, and scaption. As a supplementary aspect of our research, we conducted a preliminary exploration into potential adaptive differences in scapular kinematics among three distinct groups: athletes with scapular dyskinesis, athletes without scapular dyskinesis, and non-athletes.

2. Materials and Methods

2.1. Participants

Ethical approval to conduct this research and informed consent were obtained, respectively, from the institutional ethics committee and all subjects (athletes and non-athletes), as detailed at the end of the article.

2.1.1. Athletes

Sports clubs competing in the Portuguese Men's Volleyball Elite League and the Portuguese Men's Volleyball National Team (Portuguese Volleyball Federation) were contacted via telephone and e-mail (mostly coaches and/or managers), previously during seasons 2018–2019 and 2019–2020, to disseminate study objectives and procedures, obtain clearance to use their facilities for data collection, and assist in athletes' recruitment. A flyer, either in physical and/or digital format, explaining study objectives and procedures, including a frequently asked questions section for athletes, was distributed. Eligibility to participate was (a) being 18 or older, (b) perform at least 150 degrees of arm elevation, and (c) being involved in competitive indoor volleyball in the past 2 years. Exclusion criteria for this study was (a) history of shoulder dislocation, (b) upper extremity (UE) surgery in the past 6 months, (c) UE injury in the past month, (d) UE pain at the time of testing, including pain in cervical and thoracic spines or pain in the upper body quadrant triggered by cervical or thoracic spine mobility tests, (e) self-perceived limitation to fully participate in vigorous activities or competing sports (score 5 on any of the items of the Portuguese version of the Disabilities of the Arm, Shoulder, and Hand (QuickDASH)—sports module [23]), (f) evident abnormalities/deformities in the musculoskeletal spinal, rib cage and shoulder girdle structures (e.g., hyper-kyphosis, scoliosis, pectus excavatum, atrophy of infraspinatus muscle), and (g) lower extremity length inequality ($\geq$1.5 cm).

Following the preliminary contact with Portuguese clubs and the national team, researchers went to sports organizations to perform a structured interview and physical examination and collect biomechanical data on athletes willing to participate. Further participation was asked individually in situ. The structured interview included a detailed questionnaire assessing the duration of sports participation, amount of weekly training and competition activity, possible episodes of shoulder, elbow or wrist pain and injury or surgery, and current status of self-perceived physical performance and limitations to participate in sports (QuickDASH—sports module, Portuguese version; internal consistency, α Chronbach = 0.95; test–retest reliability, intraclass correlation coefficient (ICC) = 0.886), including shoulder/upper extremity pain (body chart mapping, 0–10 pain rating scales), weakness or fatigue, and instability (0–10 rating scales) [24–26]. Physical examination consisted of, but was not limited to, anthropometrics (e.g., height, weight), and standard clinical inspection of postural alignment and mobility of the upper body quadrant, including neurological examination of muscle power (myotomes) plus external/internal shoulder rotator muscles (manual muscle testing). Performance of scapular position and motion was assessed using the Scapular Dyskinesis Test (SDT), according to McClure et al. [27]. Athletes were rated as having normal, subtle, or obvious abnormal scapular motion patterns during bilateral arm elevation in the sagittal (flexion) and frontal planes (abduction) while holding a 1 or 2 Kg dumbbell (self-selected by participants) in their hands. This method has demonstrated satisfactory reliability for clinical use in overhead athletes (percentage of agreement, 75–82%; weighted kappa coefficients, 0.48–0.61). The first author, an academic musculoskeletal physiotherapist, conducted all interviews and physical examinations.

2.1.2. Non-Athletes

Non-athletes followed the same process of screening and examination as the athletes' group, except for surveys regarding current overhead sports participation and sports-based clinical statuses. Initially, we reached out to academic communities within sports and physical education and health sciences faculties through on-campus advertisements and personal invitations. Subsequently, we extended the invitation to the general community. The eligibility criteria for non-athletes mirrored those for the athletes' group, except that non-athletes should not have participated in competitive overhead sports, and their maximum age for participation was 34 years. We chose this upper age limit in alignment with the starting age for veterans/masters' competitions regulated by the Portuguese Volleyball Federation (35 years old). Non-athletes underwent the same screening and examination process as the athletes' group, with the exception of surveys related to current participation in overhead sports and sports-related clinical statuses.

2.2. Procedures

2.2.1. Tasks

Participants were seated and performed a series of unilateral arm elevation (ascending phase) and depression (descending phase) tasks (Figure 1a–d) while 3D shoulder kinematics were recorded. They were instructed to maintain a neutral spine against the backrest of a standard chair and perform the tasks at their own pace. Participants completed five consecutive repetitions of the task called PNF–D2–flx/ext (Figure 1a). Then, they performed two consecutive repetitions of raising and lowering the arm, with the thumb pointing upward and the elbow extended, in the frontal plane (shoulder abduction/adduction; Figure 1b), sagittal plane (shoulder flexion/extension; Figure 1c), and in the scapular plane (45° anterior to the frontal plane or shoulder scaption; Figure 1d). For PNF–D2, they began with the hand resting on the opposite hip and ended with the hand raised above and beside their head, simulating a throwing or spiking motion, while ensuring that there was no spinal movement (Figure 1a). For tasks performed in the three standard planes of motion, the starting and ending positions involved having their arms resting comfortably by their sides and then raising them to a comfortable full-arm elevation while avoiding any spinal movement (Figure 1b–d).

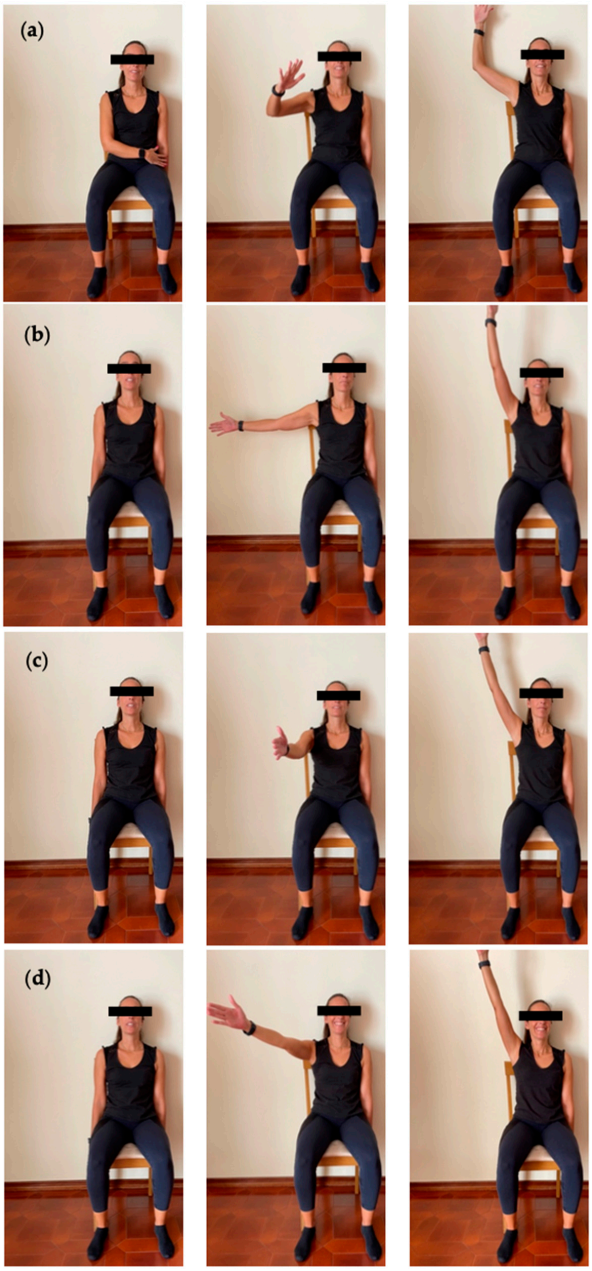

Figure 1. Tasks assessed in this research: (**a**) Diagonal 2 of proprioceptive neuromuscular facilitation (PNF–D2); (**b**) Shoulder abduction; (**c**) Shoulder flexion; (**d**) Shoulder scaption.

Participants practiced each motion, under the supervision of the research team, as often as necessary to become comfortable with the trials. After two or three attempts, all participants effortlessly completed the arm elevation/depression tasks conducted in the three standard planes of motion. Commands to maintain the thumb upwards and the elbow straight throughout the movement was necessary for some participants during preparation. For PNF–D2, most participants were given further directives to focus on a diagonal rotational movement pattern, especially external rotation of the shoulder and elbow flexion when reaching the end of PNF–D2–flx (referred to as "if you were cocking the arm to throw a ball or spike"). After 4 to 7 trial attempts, participants could complete the diagonal arm motion pattern firmly. Following a 2-min resting period, motion tracking initiated. The research team was attentive during the recordings to ensure that participants performed the movements as instructed and practiced. A re-recording was conducted if a movement task was poorly performed.

2.2.2. Kinematics

Shoulder kinematics, including the movements of the upper arm and shoulder girdle, were recorded using a 6-degrees-of-freedom electromagnetic tracking device (FASTRAK, Polhemus Inc., Colchester, VT, USA; Motion Monitor v9 software, Innovative Sports Training, Inc., Chicago, IL, USA). The system operated at a sampling rate of 30 Hz per sensor. The accuracy (root mean square) of this system is 0.3–0.8 mm for position and 0.15° for orientation when the sensor receivers are within 76 cm range of the transmitter (3SPACE FASTRAK User's Manual, Revision C. Colchester, VT; Polhemus Inc.; 2002). To capture scapular motion during arm elevation/depression, test–retest reliability and agreement parameters of the FASTRACK system are, good to excellent when measurements are taken at close intervals (standard error of the measurement (SEM) ranges = (0.9°–2.2°); intraclass correlation coefficients (ICC) ranges = (0.76–0.99)) [28], and fair to excellent, when data is acquired one week apart (SEM ranges = (1.4°–4.9°); ICC ranges = (0.22–0.92)) [29].

Participants were seated upright on a standard chair for the palpation and digitization of specific anatomical landmarks using a sensor connected to a stylus. This process was conducted to construct the local coordinate systems (LCS) for the trunk, scapula, and humerus, as defined by the International Society of Biomechanics [30]. To establish these coordinate systems, three additional sensors were meticulously positioned. One sensor was firmly affixed to the skin overlying the spinous process of the 3rd thoracic vertebra, defining the trunk LCS. Another sensor was securely attached to the superior surface of the acromion using double-sided tape, reinforced with sports tape, marking the scapula LCS. The third sensor was wrapped around the distal end of the arm with a 3 mm neoprene cuff, establishing the humerus LCS. An example of electromagnetic sensors positioning and attachments is provided in Figure 2.

Figure 2. Disposition of the trunk, scapula, and humerus electromagnetic sensor receivers on a subject.

With these sensors in place, participants then executed the arm elevation and depression tasks they had previously practiced (Figure 1a–d). During data collection session, two clinical researchers (J. F. and J. G.) conducted all digitisations and provided standardized instructions, while a third researcher (N. M.) operated the computer. Subsequently, joint angles were calculated and expressed as Euler angle decompositions, describing the relative orientation of the scapula with respect to the thorax. The coordinate system for scapular rotations was defined with the y-axis pointing upward, the x-axis extending from left to right, and the z-axis pointing backward. The $YX'Z''$ Euler sequence was employed to convey scapular orientation, with the first rotation representing internal (positive)/external rotation (IR/ER) of the scapula along the y-axis, the second rotation signifying upward (negative)/downward rotation (UR/DR) around the twice-rotated scapular x-axis, and the third rotation indicating anterior (negative)/posterior tilting (AT/PT) around the rotated scapular z-axis.

Data were filtered using a lowpass 8 Hz Butterworth filter, exported to MATLAB (MathWorks Inc., Natick, MA, USA, vR2016a) and then reduced to increments of 15° from minimum (initial position) to 120° of humero-thoracic (HT) elevation (final position). For presentation and clinical interpretability purposes, scapular upward rotation was multiplied by -1 (thereby later shown as positive in Figure 4). Left-handed, rotations of the left side were transformed by appropriate geometrical calculation for projection on the right side. Repetitions of each task were averaged for ulterior analysis. For PNF–D2–flx/ext (Figure 1a), repetitions 1 and 5 were removed, having been averaged repetitions 2–4. For shoulder abduction/adduction, flexion/extension, and scaption (Figure 1b–d), this represents repetition 1 and 2.

2.3. Data Analysis

Statistical analyses were conducted using IBM SPSS, version 27 (Chicago, IL, USA). A mixed-model analysis of variance (ANOVA) of phase (ascending/arm elevation and descending/arm depression), HT angle (minimum, 30°, 45°, 60°, 75°, 90°, 105° and 120°) and task (PNF–D2, and shoulder abduction, flexion and scaption), as within-subject variation factors, and group (athletes "normal", athletes with scapula dyskinesis, and non-athletes "normal"), as between-subject variation factor, with interaction (phase × HT angle × task × group), was performed for each scapular rotation. A separate ANOVA was also performed for each phase and task condition. The Greenhouse–Geisser correction was used to adjust the degrees of freedom when the sphericity assumption (Mauchly's test) was violated. When a significant interaction was present, pairwise comparisons were conducted using Bonferroni correction for multiple comparisons. The significance level was set at 0.05.

To complement inferential statistics, eta square partial (η_p^2) was calculated. For $\eta_p^2 > 0.5$ the effect size is deemed very large; $0.25 < \eta_p^2 \leq 0.50$ is large; $0.05 < \eta_p^2 \leq 0.25$ is moderate; and for $\eta_p^2 \leq 0.05$ the effect is small.

3. Results

3.1. Participants

3.1.1. Athletes

Eight sporting clubs and the Portuguese national team replied to the call for participants; nevertheless, data ended up being collected in four clubs and the Portuguese national team. Two clubs stopped answering after the first meeting (no reason given). One club backed down after agreeing to participate due to internal instability of management and coaching staff. Another withdrew its willingness to collaborate after rumors of the beginning of the first wave of COVID-19, in Portugal, had emerged in the media (February–March 2020). Athletes participating in the study while representing the Portuguese national team or another club in one season did not participate a second time when visiting their current club.

Thirty-one volleyball players volunteered to participate in this study. After interviewing and screening, nine athletes were excluded due to (a) pain in the dominant/throwing shoulder at the time of data collection (n = 8) and, (b) visible atrophy of the infraspinatus muscle of the dominant arm and reduced shoulder external rotation strength (n = 1). All eligible athletes (n = 22) selected the 2 Kg dumbbell for performance of the SDT. Eleven showed abnormal scapular position and motion of the dominant/throwing shoulder (subtle, n = 6; obvious, n = 5) whereas another 11 exhibited normal scapular position and motion of both shoulders. The abnormal scapular position and motion (or scapular dyskinesis (ScDk)) group was composed by five attackers, four liberos and two setters (henceforth referred to as athletes with ScDk). The normal scapula group comprised seven attackers, three setters and one libero (hereafter simply referred to as athletes). The dominant throwing arm was the right in all but three players. The mean (±standard deviation) hours of practice were 17.91 ± 2.88 in the group of athletes without and 16.90 ± 2.88 in athletes with ScDk ($p = 0.216$). Demographics and anthropometrics of the players are presented in Table 1.

Table 1. Anthropometrics (height, body mass and BMI) and demographics (age) of the participants. Data is presented as mean ± standard deviation.

Variable	Athletes (n = 11)	Athletes w/ScDk (n = 11)	Non-Athletes (n = 27)	p	η^2
Age (years)	25.55 ± 5.43	23.1 ± 4.99	22.36 ± 2.41	0.098	0.099
Height (m)	1.88 ± 0.09	1.84 ± 0.07	1.78 ± 0.07	<0.001 *	0.269
Body mass (Kg)	83.94 ± 9.38	78.55 ± 8.92	75.25 ± 9.60	0.044 *	0.127
BMI (Kg/m^2)	23.71 ± 2.72	23.95 ± 2.71	23.85 ± 2.68	0.828	0.019

*, significant group differences between athletes and non-athletes (Bonferroni post-hoc test); m, meter; Kg, kilogram; ScDk, scapular dyskinesis; w/, with, η^2, eta square.

3.1.2. Non-Athletes

Twenty-seven non-athletes (six from the academic community) agreed to participate, and all met the inclusion and exclusion criteria. All except three were right-handed. Twenty-one (n = 21) were engaged (up to three times a week) at a recreational level in football (n = 7), basketball (n = 5), bodyboard (n = 2), karate (n = 2), swimming (n = 2), triathlon (n = 1), canoeing (n = 1) and tennis (n = 1). All (n = 27) but one selected the 2 Kg dumbbell for performance of the SDT. Demographics and anthropometrics of the non-athletes are presented in Table 1.

3.2. Three-Dimensional Scapular Kinematics

In general, the scapula moved into external rotation, upward rotation, and posterior tilt during arm elevation, and towards internal rotation, downward rotation, and anterior tilt during arm depression both for the shoulder movements in the three orthogonal planes of arm elevation and the diagonal arm elevation (PNF–D2) tasks, albeit some variations were found (Figures 3–5), as later described. Mean differences between ascending (arm elevation) and descending (arm depression) phases were mostly low and frequently dependent on task and HT angle (IR/ER < 6°; UR/DR < 3°; AT/PT < 3°). For details regarding interaction effects, see Supplementary Material.

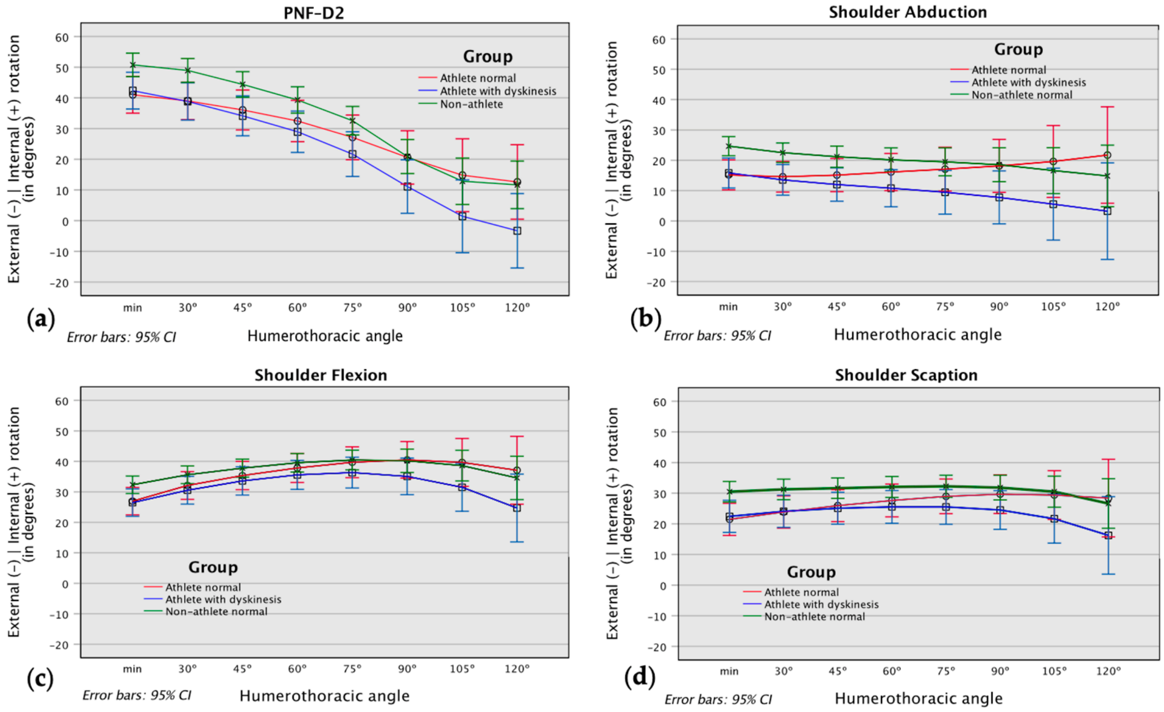

Figure 3. Scapular external (negative)/internal (positive) rotation throughout humero-thoracic arm elevation on each study group during: (**a**) Diagonal 2 of proprioceptive neuromuscular facilitation (PNF–D2); (**b**) Shoulder abduction; (**c**) Shoulder flexion; (**d**) Shoulder scaption. Only elevation phase is presented (descending phase is displayed in Supplementary Material).

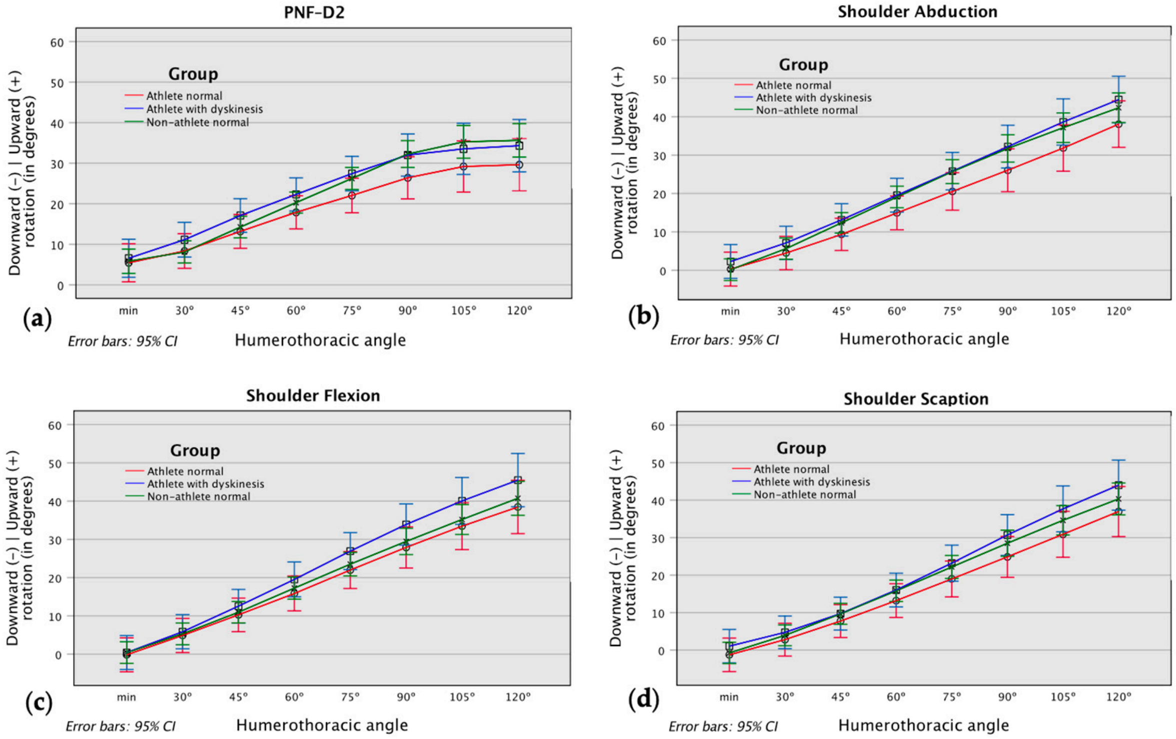

Figure 4. Scapular downward (negative)/upward (positive) rotation throughout humero-thoracic arm elevation for each study group during: (**a**) Diagonal 2 of proprioceptive neuromuscular facilitation (PNF–D2); (**b**) Shoulder abduction; (**c**) Shoulder flexion; (**d**) Shoulder scaption. Only elevation phase is presented (descending phase is displayed in Supplementary Material).

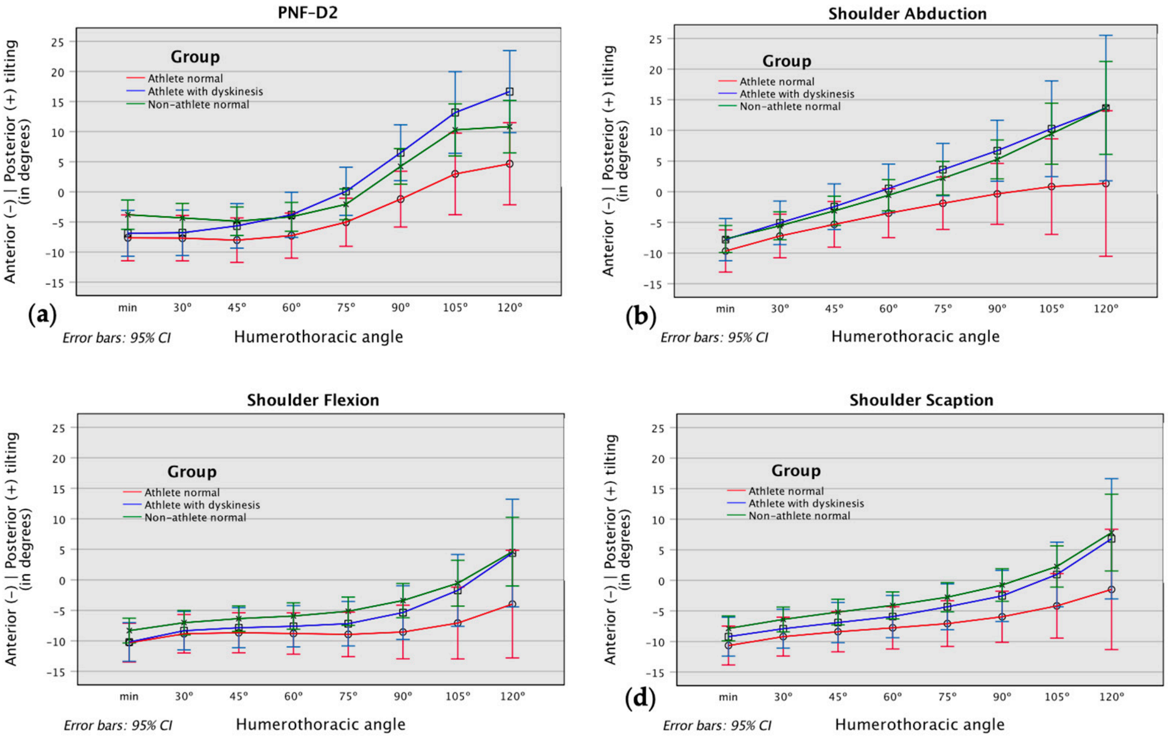

Figure 5. Scapular anterior (negative)/posterior (positive) rotation throughout humero-thoracic arm elevation for each study group during: (**a**) Diagonal 2 of proprioceptive neuromuscular facilitation (PNF–D2); (**b**) Shoulder abduction; (**c**) Shoulder flexion; (**d**) Shoulder scaption. Only elevation phase is presented (descending phase is displayed in Supplementary Material).

3.2.1. Scapular Internal/External Rotation

The scapula consistently moved into external rotation during arm elevation and internal rotation during arm depression in all groups, for PNF–D2 (mean angular displacement, ~40°; Figure 3a), but variations were found regarding the other tasks ("main effect" of task, $F_{2.5,113.9} = 134.281$, $p < 0.001$, $\eta_p^2 = 0.745$; interaction effect HT angle × task, $F_{3.7,171.3} = 156.089$, $p < 0.001$, $\eta_p^2 = 0.772$). During shoulder abduction (Figure 3b), the scapula underwent external rotation during arm elevation and internal rotation during arm depression, on average, ~15° in athletes with ScDk and ~11° in non-athletes. In athletes, the opposite was observed. In this group, the scapula internally rotated during arm elevation and externally rotated during arm depression, on average, ~5°, nevertheless no "main effect" for group was found ($F_{2,46} = 2.846$, $p = 0.068$, $\eta_p^2 = 0.110$). In shoulder flexion, the scapula moved into internal rotation up to 75° of HT elevation, in athletes with ScDk (~10°) and non-athletes (~9°), and 90°, in athletes (~14°), and then externally rotated, respectively, ~7°, ~6° and ~3°, on average (Figure 3c), although no statistical differences were observed (phase × HT angle × group, $F_{3.8,88.2} = 0.235$, $p = 0.912$). During shoulder scaption (Figure 3d), the movement pattern of the scapula was similar to that of shoulder flexion, but, on average, with smaller angular displacement (all groups, IR, ~4° and then ER, ~4°). Differences were not statistically significant though (phase × HT angle × group $F_{5.4,124.2} = 0.516$, $p = 0.777$).

No interaction of phase × HT angle × task × group effects ($F_{11.9,272.5} = 1.412$, $p = 0.161$, $\eta_p^2 = 0.058$) was found.

3.2.2. Scapular Upward/Downward Rotation

As the HT angle increased during arm elevation, the scapula progressively upwardly rotated, in all task conditions. Conversely, as HT angle decreased (arm depression), the scapula downwardly rotated, in all task conditions. The steepness of upward rotation was noticed after 45° of HT elevation for PNF–D2, shoulder flexion and shoulder scaption (Figure 4a,c,d). In shoulder abduction, marked upward rotation started earlier (Figure 4b). On average, the magnitude of scapular upward/downward rotation (mean ± sd) was smaller ("main effect" of task, $F_{2.1,97.8} = 8.122$, $p < 0.001$, $\eta_p^2 = 0.150$) in PNF–D2 (33.9° ± 10.6°) than in shoulder abduction (42.2° ± 9.9°), flexion (41.3° ± 11.3°), or scaption (40.7° ± 11.0°). An interaction effect of HT angle × task was observed ($F_{3.5,161.5} = 45.899$, $p < 0.001$, $\eta_p^2 = 0.499$). Pairwise comparisons revealed significant differences (3°–6°) between HT angles up to 45° and then from 105° to 120° (−3°–−9°) in PNF–D2 and the other task conditions ($p \leq 0.003$).

No interaction effect of phase × HT angle × task × group was found ($F_{13.0,299.0} = 0.753$, $p = 0.710$, $\eta_p^2 = 0.032$).

3.2.3. Scapular Anterior/Posterior Tilting

As the HT angle increased (arm elevation), the scapula moved from anterior into posterior tilting, in all task conditions and groups (Figure 5). As the HT angle decreased (arm depression), the scapula moved from posterior into anterior tilting, in all task conditions and groups. A main effect of task ($F_{2.1,55.2} = 55.232$, $p < 0.001$, $\eta_p^2 = 0.546$) and a HT angle × task interaction ($F_{2.6,120.4} = 17.474$, $p < 0.001$, $\eta_p^2 = 0.275$) was found. Post-hoc comparisons revealed statistical mean differences between PNF–D2 (3°–12°) and shoulder abduction (4°–10°) with shoulder flexion and shoulder scaption, from 60° to 120° of HT angle ($p \leq 0.007$).

On average, athletes showed less scapular tilting (4°–5°) than athletes with ScDk and non-athletes, in all task conditions and HT angles (Figure 5a–d), but differences were not significant ($F_{5.2,120.4} = 1.193$, $p = 0.316$, $\eta_p^2 = 0.049$).

No interaction effect of phase × HT angle × task × group was found ($F_{11.6,266.8} = 1.307$, $p = 0.216$, $\eta_p^2 = 0.054$).

4. Discussion

We specifically examined a diagonal movement pattern of arm elevation/depression (PNF–D2–flx/ext), which is distinct from traditional arm elevation/depression tasks conducted in the three standard planes of motion—shoulder abduction, shoulder flexion, and shoulder scaption– and has its unique scapular kinematics. Although the four arm elevation tasks generally exhibited a scapular motion pattern of external rotation, upward rotation and posterior tilting (Figures 3–5) during arm movement, the scapula exhibited less upward rotation (Figure 4) and more posterior tilt (Figure 5) in PNF–D2 compared to shoulder abduction, flexion, or scaption. Particularly noteworthy was the consistent transition from internal rotation to external rotation (and vice versa) of the scapula in PNF-D2 (Figure 3a). This transition was more prominent than in shoulder flexion (Figure 3c), shoulder scaption (Figure 3d), and, to a lesser extent, shoulder abduction (Figure 3b). However, it is worth noting that differences between groups were not statistically significant across all tasks.

Studies examining 3D scapular kinematics during shoulder movements beyond the conventional full or near-full arm elevation in the sagittal, frontal, and scapular plane are scarce. An early research by Amasay and Karduna [4] was among the first to compare 3D scapular kinematics between functional tasks (such as reaching for a car seat belt or reaching for an overhead shelf) and humeral elevation movements constrained to a specific plane of motion. In their study, Amasay and Karduna discovered significant differences in all scapular rotations for most task conditions, even when the humero-thoracic elevation and plane of elevation angles were the same. The functional tasks they examined, reaching for an object on the right side ("right side") and reaching for an object on the left side ("left side") with the right hand are conceptually similar, to some extent, to the functional movement task we employed in our research (i.e., PNF–D2). The authors noticed that these functional tasks resulted in larger scapular external rotation angles than the constrained task. However, for scapular upward rotation and posterior tilt, the constrained arm elevation task exhibited, on average, larger angles, with differences of up to 5.6° and

2.3°, respectively. The findings of our study are somewhat in line with those of Amasay and Karduna's research. We also observed reduced upward rotation in PNF–D2 when compared to the three constrained planes of arm elevation tasks; however, it is important to note that this difference was more pronounced at higher angles of humero-thoracic (HT) elevation (between 90° to 120°). At a 30° HT elevation, which corresponds to the angle Amasay and Karduna used to compare "right side" and "left side" with constrained arm elevation, PNF–D2 actually exhibited larger scapular upward rotation (mean [95%CI]) than shoulder abduction (+4.3° [1.7°–6.9°], $p < 0.001$), shoulder flexion (+4.9° [2.6°–7.1°], $p < 0.001$), or shoulder scaption (+6.0° [3.8°–8.3°], $p < 0.001$). When contrasting scapular external rotation and posterior tilting with the aforementioned study, the comparison becomes more intricate, especially concerning scapular external rotation. This complexity arises because we found significant interaction effects of HT angle × task in both scapular rotations. At 30° of HT elevation, nevertheless, scapular external rotation was, on average, significantly larger in PNF–D2 than in shoulder abduction (+18.6° (15.0°–22.1°), $p < 0.001$), and shoulder scaption (+9.1° (5.8°–12.4°), $p < 0.001$), but it was comparable to shoulder flexion (+1.5° (−1.6°–4.5°), $p > 0.05$). The mean differences in scapular posterior tilting, at 30° of HT elevation, between PNF–D2 and shoulder flexion and shoulder scaption were very low (<1°, $p > 0.05$). However, there was a statistically significant difference when comparing PNF–D2 with shoulder abduction (−2.1° (−4.1°–−0.1°), $p = 0.034$). It is important to consider that PNF–D2 involves a combination of moving from the left side to the right side while elevating the arm above shoulder height (and vice-versa). This complex movement pattern is likely to require different muscle recruitment and coordination compared to the simpler "left side" and "right side" tasks studied by Amasay and Karduna, which targeted lower than shoulder height. Therefore, the conflicting results in 3D scapular kinematics between studies are not surprising. Comparing our findings with other studies that have investigated scapular kinematics during functional tasks is even more challenging, because several factors differentiate our study. Unlike some previous studies [5,6], we specifically examined a diagonal movement pattern of arm elevation, which is distinct from other functional tasks and has its unique scapular kinematics. Additionally, some studies did not include comparisons between constrained and functional humeral movements [7,9], making it difficult to draw direct parallels with our results. Furthermore, in certain studies, detailed descriptions of scapular kinematics throughout the full movement were not provided [7–9], limiting our ability to make comprehensive comparisons.

A recent systematic review focused on overhead athletes with and without rotator cuff tendinopathy and highlighted that the existing primary studies (comprising nine studies and a total of 332 athletes) have predominantly investigated differences and adaptations in 3D scapular kinematics during constrained arm elevation, with a particular emphasis on the scapular plane (or scaption) [3]. In the absence of a widely accepted test for evaluating functional upper extremity motion, the scaption task (involving arm elevation at an angle of 30 to 45 degrees anterior to the frontal plane) has been employed as a testing protocol to assess shoulder kinematics across various populations, including the general population and specific groups, like athletes. This choice is based on the recognition that many upper extremity activities impose arm movements that fall between the sagittal and frontal planes. However, scapular kinematics observed during shoulder scaption may not be easily extrapolated to a functional diagonal movement pattern, such as those involved in throwing motions, as demonstrated in our study. This holds true for all scapular rotations, especially those referred to as secondary or accessory scapular rotations (internal/external rotation and, to a lesser extent, anterior/posterior tilting), as well as the primary scapular rotation strongly coupled to arm elevation (upward/downward rotation). This finding holds clinical significance as variations in scapular internal/external rotation (ranging from 5.6° to 7.7°) and anterior/posterior tilting (5.2°) have been observed during simulated activities, like volleyball spikes among injured and non-injured players [18]. Additionally, differences in scapular internal/external rotation (ranging from 2.0° to 6.0°) have been noted between the injured and contralateral shoulder during the late cocking phase of a simulated throwing motion in baseball players [17]. Moreover, tennis players with a history of shoulder issues exhibited alterations in scapular upward/downward rotation (approximately 5°) during the late cocking position of a tennis serve compared to their non-injured counterparts [31]. It remains uncertain whether these observed scapular kinematic differences during complex movements, such as throwing motions, are also detectable during standard arm elevation tests typically constrained to a single plane of arm elevation, as is often assumed in clinical practice. This raises important questions about the efficacy of incorporating athletic overhead functional movement patterns, like those studied here, into the clinical examination of scapular function in athletes. Such an approach may potentially enhance the diagnostic process, guide rehabilitation interventions, and inform return-to-play decisions following a shoulder injury. These considerations warrant further investigation in future research endeavors.

A secondary objective of this study was to evaluate whether there were significant differences in the PNF-D2 task between athletes with and without dyskinesis. This was a preliminary evaluation that could guide future, more comprehensive research. Future studies with extended recruitment periods and larger sample sizes are needed to further investigate the scapular (mal)adaptive movement patterns resulting from repetitive unilateral overhead throwing. Whether altered scapular kinematics is detrimental to shoulder function, poses a risk factor for shoulder injuries and pain, or is just a normal adaptation to chronic throwing exposure is the subject of ongoing debate [1,2,32–35] and conflicting findings [3,35–39] in the literature. In our preliminary analysis, we did not observe statistically significant differences in scapular motion between athletes with and without scapular dyskinesis, as well as non-athletes. On average, any differences between these groups tended to be more pronounced for scapular internal/external rotation (up to 8.5°), followed by anterior/posterior tilting (up to 5.6°), and were relatively smaller for upward/downward rotation (up to 4.2°). Our findings appear to contradict those of a study conducted by Seitz et al. [40], which examined 3D scapular orientation in a mixed group of overhead sports athletes, including volleyball, water polo, and swimming. In their research, athletes with scapular dyskinesis (n = 14), identified using a similar screening method to ours, exhibited, on average, reduced scapular external rotation (10.7°, $p = 0.036$) at 90° of humero-thoracic elevation performed in the sagittal plane (shoulder flexion) compared to athletes without scapular dyskinesis (n = 11). Intriguingly, our study found fewer differences in scapular motion at the 90° angle of humero-thoracic elevation between volleyball players with and without dyskinesis across all tasks (Figure 3). These disparities between our findings and those of Seitz et al. [40] could potentially be attributed to differences in sample characteristics (mixed-sex and overhead sports participants with only apparent dyskinesia [40] vs. male volleyball players with both subtle and apparent dyskinesia in an equal proportion in our study) and task protocols (arm positioning at 90° of humero-thoracic elevation [40] vs. continuous arm elevation from rest to full arm elevation in our study). Another study [41] that employed the same method for diagnosing scapular dyskinesis also identified significant differences in scapular orientation among male high school pitchers. In this study, individuals with dyskinesis (n = 15; including five with obvious dyskinesis and 10 with subtle dyskinesis) displayed distinct scapular positioning and motion compared to those with clinically determined normal scapular function (n = 18). Utilizing an optical system to capture 3D scapular kinematics, researchers observed that the pitching arms with scapular dyskinesis exhibited, on average, greater scapular internal rotation (3.8°, $p = 0.020$, $d = 0.80$) compared to the pitching arms of their non-impaired counterparts. These differences were associated with a reduced maximum shoulder rotation velocity during pitching (−369°/s, $p = 0.016$, $d = 14.66$), supporting the thesis that scapular dyskinesis could be detrimental to shoulder athletic performance. We should, however, exercise caution when interpreting these findings, as the 3D scapular orientation was only recorded with the arms at rest and not during the actual throwing motion in Bullock et al.'s study [41]. Velocity was not a kinematic variable of interest in our study, nevertheless we observed that at higher degrees of humero-thoracic elevation (75° to 120°), typically corresponding to the cocking and acceleration phases of throwing, differences in scapular external rotation between athletes with and without dyskinesia, on average, increased (Figure 3a, PNF–D2). It is important to note that executing a throwing motion at maximum angular velocity places significant demands on the shoulder complex. Overhead athletes with scapular dyskinesis may exacerbate their ability to control scapular orientation when subjected to extreme loads on their throwing shoulder, especially at higher HT elevation angles [40]. This effect could be attributed to deficits or imbalances in scapular muscle strength [40]. As such, we hypothesize that combining the PNF-D2 movement pattern with resistance from free weights or elastic bands may enhance the differentiation between groups and provide deeper insights into the distinctions between positive and maladaptive scapular adaptations, as well as the mechanisms of throwing-related injuries in predominantly unilateral overhead sports athletes. Further research in this direction is therefore warranted.

This study has several limitations that should be acknowledged. Firstly, our sample consisted exclusively of male players, which limits the generalizability of our findings to female players and to players with existing shoulder symptoms or injuries. Secondly, our group of athletes with scapular dyskinesis included both subtle (55%) and obvious dyskinesia (45%). The inclusion of participants with subtle dyskinesia may have potentially blurred differences between athletes without dyskinesia, and this should be considered in future research. Thirdly, the robustness of our findings is constrained by the small sample size. An "a priori" sample size calculation indicated a total sample size of 102 subjects (34 per group) for conducting a repeated measures ANOVA with three groups, four measurements, an effect size of 0.25, an alpha-error probability of 0.05, and a power of 0.80. However, due to challenges in recruiting professional athletes, we initially sought to gather preliminary data to assess the relevance of this research direction before committing more substantial human and material resources to further studies. Lastly, data collection did not occur during the same period of the competitive season, which could have influenced the results, as scapular kinematics may vary throughout a competitive season [42,43].

5. Conclusions

This study revealed statistically significant distinctions in 3D scapular orientation when comparing diagonal humeral elevation (PNF–D2) to humeral elevation in the traditional planes of motion (shoulder abduction, shoulder flexion, and shoulder scaption). However, no statistically significant differences were observed between athletes with clinically diagnosed scapular dyskinesis and non-athletes without this impairment. These findings are preliminary and underscore the need for further research in this area to clarify whether including a functional arm movement pattern when evaluating scapular position and movement in overhead athletes may be clinically relevant.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app131910691/s1, Figure S1: Scapular external (negative)/internal (positive) rotation throughout humero-thoracic arm elevation and depression on each study group; Figure S2: Scapular downward (negative)/upward (positive) rotation throughout humero-thoracic arm elevation and depression on each study group; Figure S3: Scapular anterior (negative)/posterior (positive) tilting throughout humero-thoracic arm elevation and depression on each study group.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author. Data is not publicly available as this investigation is still in progress.

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