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First-Division Softball Players with Shoulder Injuries Exhibit Upper-Body Compensatory Strategies Compared to Healthy Controls: A Case Study Using Wearable Inertial Sensors

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Abstract: The aim of this study was to assess the kinematic differences in the upper limb and trunk between healthy and shoulder-injured softball position (non-pitchers) players. Eleven first-division softball players (mean age: 25.9 ± 8.1 years) were enrolled: five players who had experienced a shoulder injury with consequent surgery (time from surgery to test: 0.9 years) and six healthy matched controls. The position players performed their typical throw motor task after receiving the ball from a buddy. Wearable inertial sensors (Xsens MTw Awinda) were used to collect the kinematical data on the shoulder, elbow, and trunk. Peak joint kinematics and range of motion (ROM) were compared between healthy and injured players separately for the “Pickup” and “Pass” phases. In the pickup phase, a higher internal/external rotation ROM of the shoulder was found in healthy players than in the injured ones ($p = 0.016$). Similarly, elbow flex/extension ROM was higher in the healthy players ($p = 0.039$). A higher peak of trunk flexion was also found in healthy players than the injured ones ($p = 0.002$). In the pass phase, shoulder internal/external rotation, adduction/abduction, and flex/extension ROM were greater in healthy than injured players ($p = 0.050$, $p = 0.001$, and $p = 0.007$, respectively). Healthy players also showed a higher elbow peak flexion ($p = 0.022$). The shoulder-injured players showed a lower ROM than the healthy ones during both the pickup and pass phases of a throw motor task. Despite being cleared to return to play, the injured players could voluntarily or unconsciously perform the motor task in a more conservative way than the healthy controls.

Keywords: wearable inertial sensors; shoulder injury; softball; kinematics; ecological validity

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1. Introduction

Softball is widely played across the world. It is particularly prominent in the United States, Japan, Canada, Australia, and several European countries, such as the Netherlands and Italy [1]. According to the Statista Research Department [2], in 2021, the number of softball athletes in the U.S. reached 8.1 million. However, the physical demands of softball, involving intense movements, such as pitching, batting, and sprinting, lead to both acute injuries (i.e., sprains and fractures) and overuse injuries (i.e., shoulder or elbow strains) [3].

In particular, upper-limb injuries related to throwing movements are the most common in softball [4–7]. Continuous softball practice can lead to chronic overuse injuries, particularly in the shoulder and elbow joints, due to repetitive stresses from repeated throwing motions [8].

The most common shoulder injuries among softball players are muscle–tendon strain, tendinitis, and subluxation [9,10]. In severe cases, upper-body injuries may necessitate surgery, extending the rehabilitation period and return-to-play time. Moreover, after severe injuries or surgery, it is expected that players may alter their throw kinematics due to disuse or changes in muscular and tendon strength balance [11,12].

In general, athletes often exhibit compensatory movements following injuries, which can alter their kinematics in order to maintain their performance, despite physical limitations [13]. These adaptations can vary depending on the type of injury sustained and the specific demands of the sport. For example, wrist injuries in basketball players may alter shooting movements, decreasing their performance [14]. In addition, athletes have shown biomechanical deficits during non-specific motor tasks, such as the vertical jump test [15]. While these adaptations may benefit their short-term performance, they can lead to additional stresses on other body parts, potentially resulting in secondary injuries [3,16].

In light of this, to design and prescribe a sport-specific strength and conditioning program aimed at reducing injury risk, enhancing performance, and improving health and lifespan, it is crucial to understand how injuries can influence the kinematics of softball position players once they return to play [7,8,17,18].

While many studies on softball primarily concentrate on the windmill pitch executed by pitchers [6,7,19–21], it is important to note that pitchers are not the sole players susceptible to injuries. Indeed, injuries sustained during softball practice are more commonly linked to throwing activities not directly related to pitching, such as those carried out by position (non-pitchers) players [8,9].

The aim of this study was to assess the kinematic differences in the upper limb and trunk between healthy and shoulder-injured softball position players. It was hypothesized that residual kinematical differences and compensatory strategies would emerge in players that had suffered a shoulder injury compared to the healthy ones.

2. Materials and Methods

This was a cross-sectional study that compared the kinematics of two groups of softball position players at one time point. The present study received approval from the Bioethical Committee of the University of Bologna (ID: 0387977; date: 28 December 2023). Informed consent was obtained from each softball player prior to enrollment. This study was executed in accordance with the Helsinki Declaration.

2.1. Sample

A cohort of 11 first-division female softball players (mean age: 25.9 $\pm$ 8.1) was enrolled in this study. Five players experienced superior labrum and anterior and posterior (SLAP) lesions to the shoulder of their dominant arm with consequent surgery. The time from surgery to test was 0.9 $\pm$ 0.4 years. Six players with no previous shoulder injuries were enrolled as matched controls. All players actively involved in softball training and competitions, without upper-limb injuries in the past six months, were included in this study. Pain, current injuries, or conditions that might impair throwing performance were considered exclusion criteria.

2.2. Design

All the trial assessments were performed in January 2024. After a proper 10 min warm up for throwing [9], guided by an experienced coach (A.M.), the players were equipped with a set of 11 wearable inertial sensors (Xsens MTw Awinda, Movella, Enschande, The Netherlands), placed on the head, shoulders, sternum, pelvis, upper arms, forearms, and hands by a single experienced user (S.D.P.) [22]. This system is designed and validated for high accuracy when measuring joint angles and kinematics during dynamic activities, including throwing [23,24]. Then, a dynamic calibration procedure (standing still + walking) was performed according to the manufacturer's guidelines. After the calibration procedure, the players were asked to perform a typical throw motor task: players received the ball from a buddy (15 mt away), picked up the ball from the ground, and threw the ball back to the same buddy. This movement resembles the most typical tasks of position players, which include throwing the ball back to the pitcher and to bases during steal attempts or pickoff plays. The players completed 10 valid throw trials, and the three with the highest spin velocity were retained for further analysis. Kinematic data on the shoulder, elbow, and trunk were collected using a sample rate of 100 Hz. The data acquisition process was overseen by A.M., an experienced softball coach.

2.3. Data Processing

The motor task was divided into two phases: the "Pickup" phase, which starts from ball grabbing to reaching the throw position, and the "Pass" phase, which covers the motion from the hand far back to the completion of the throw. XSENS Analyze software was used to identify valid trials (highest hand velocity [25,26]) and specific events defining the different stances of interest.

Primarily, the data from the different exercises were separated in a custom MATLAB script (v R2020a, The MathWorks, Natick, MA, USA) [7,17]. The phases were extracted from the data obtained during the data collection and normalized using 3 points of interest. The initial point was defined as the beginning of the stance, set at the 0% frame, while the endpoint of the stance was established as the 100% frame. An additional point was used to define the 50% frame of the stance. The different points used are referenced in Table 1 and Figure 1.

Table 1. Description of the different phases of the movement and their implementation in the MATLAB scripts.

Phase of the Movement	% of the Overall Time Window	Event (General Definition)	Implementation
Pickup	0	Player starts to move	40% of the mean CoM speed between frame 1 and the pickup 50%
	50	Ball grab	Minimum CoM position along the z axis
	100	Player getting in throw position	Mean CoM position between the maximum and the minimum CoM positions
Pass	0	End of the pickup	End pickup
	50	Hand far back (Start of throw)	Elbow further back
	100	Ball thrown	Maximum hand position along the x axis + 50 ms

Note: center of mass = CoM.

For the purpose of this study, kinematics for shoulder, elbow, and trunk were kept and analyzed. The joint coordinate system used in this study adhered to the recommendations set forth by International Society of Biomechanics (ISB), wherein positive rotations are defined as shoulder abduction, internal rotation, flexion, elbow flexion, and internal rotation (pronation) [27].

For each phase, the peak values defined as the maximum rotation value, the minimum rotation value, and the range of motion (ROM) were computed. The whole data processing was carried out in MATLAB.

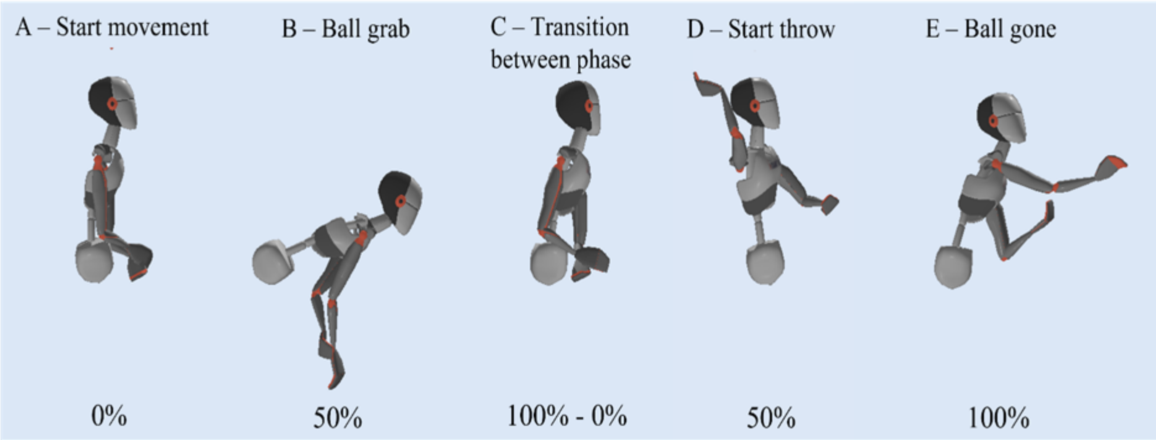

Figure 1. Player movement decomposition during the stance in the pickup and pass exercises. Pickup starts at A and ends at C, while the pass starts at C and ends at E. The player starts to move at point A to catch the ball on the ground at point B before getting into position to start the pass at point C. From point C, the player starts the throw from the position of point D, and the pass is completed when the ball is released at point E.

2.4. Statistical Analysis

The normal distribution of the data was verified through the Shapiro–Wilk test. The normally distributed continuous data were presented as mean ± standard deviation with a 95% confidence interval (CI), the categorical data were presented as a percentage over the total, while the non-normally distributed data were presented as median and interquartile range (IQR).

Student's *t*-test was employed to compare the characteristics, such as age, height, weight, BMI, and year of experience playing softball between the two groups. The Mann–Whitney U test was used to inspect the differences in upper-limb and trunk kinematics between the healthy and injured athletes. A $p < 0.05$ was considered statistically significant. Z-scores were used to compare each kinematic variable in a uniform space (radar plot) between healthy and injured softball players. The Z-score quantifies the number of standard deviations from the mean. For this analysis, the mean value for the Z-score was established based solely on the average measurements from the healthy group, allowing for a standardized comparison with injured players.

All the analyses were performed in MATLAB. No a priori power analysis was performed, due to the exploratory nature of the pilot study.

3. Results

The comparison of the samples' characteristics did not show significant differences between the healthy and shoulder-injured groups (Table 2).

Table 2. Comparison of samples' characteristics.

	Injured Players	Healthy Players	*p* Value
Age (y.o.)	23.9 ± 6.8	27.5 ± 9.4	n.s.
Height (cm)	169.4 ± 3.6	165.5 ± 5.9	n.s.
Weight (Kg)	70.8 ± 13.9	62.7 ± 8.7	n.s.
BMI (Kg/m^2)	15.8 ± 7.5	18.8 ± 9.3	n.s.
Years of experience	15.8 ± 7.5	18.8 ± 9.3	n.s.
Years from injury	2.6 ± 1.8	-	-
Years from surgery	0.9 ± 0.4	-	-

Data are presented as mean ± standard deviation. Note: n.s., not significant.

In the pickup phase (Figure 2), the shoulder showed a wider internal/external rotation ROM in healthy players than in the injured ones ($p = 0.016$). The same results were observed for the elbow flex/extension and internal/external rotation ROM ($p = 0.039$ and $p < 0.001$, respectively), and trunk abduction–adduction ROM ($p = 0.014$). Moreover, healthy players showed a higher peak of trunk flexion than the injured ones ($p = 0.002$) (Table 3). Joint kinematics (minimum and maximum peak angles) and SPM1D analysis of the pickup phase are presented in the Supplementary Materials (Figures S1–S3; Table S1).

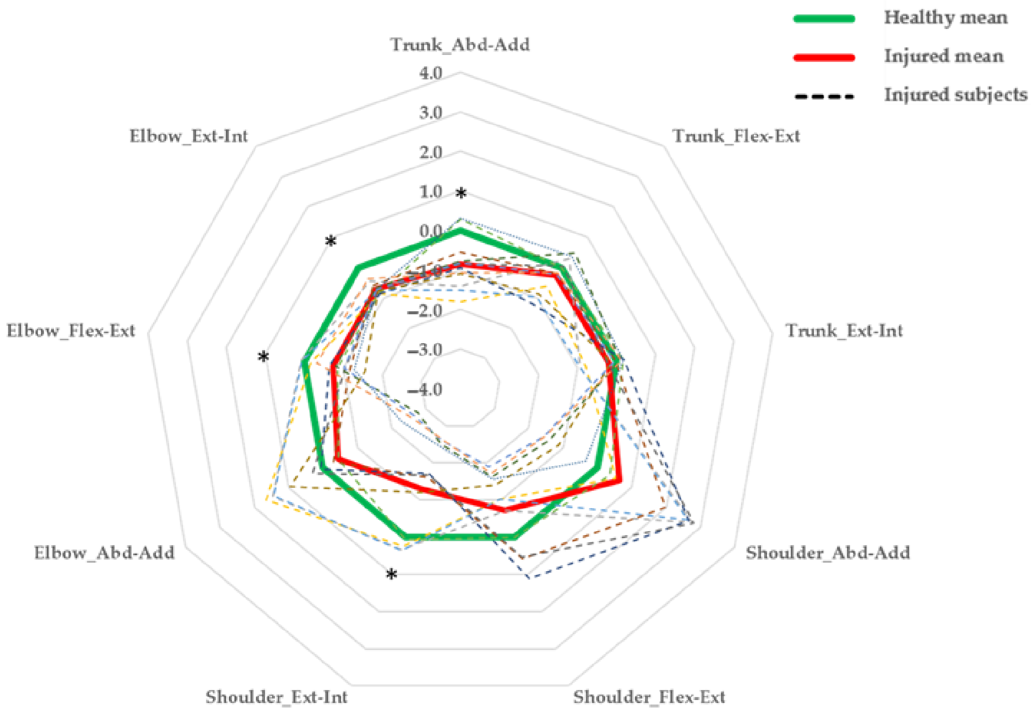

Figure 2. A radar chart of the joint ROM kinematic comparison between healthy and injured players, standardized using Z-scores, during the pickup phase. The black line represents the normalized mean ROM of healthy players, while the red line represents the ROM of injured players. Each dashed line corresponds to the ROM of individual injured players. Note: * = p-value < 0.05. Abd–Add: abduction–adduction, Flex–Ext: flexion–extension, Ext–Int: external–internal rotation.

Table 3. ROM parameters extracted for the trunk, shoulder, and elbow during the pickup phase for the healthy and injured players.

Pickup					
Joint (°)	**Rotation**	**Healthy**	**Injured**	**Diff [95% CI]**	***p***
Trunk	Abd–Add	17.6 (8.2)	11.1 (3.5)	**6.5 [−2.3, 15.3]**	**0.014**
	Flex–Ext	22.1 (10.0)	21.1 (6.3)	1.0 [−7.8, 9.8]	n.s.
	Ext–Int	18.8 (14.1)	19.3 (4.8)	−0.5 [−9.3, 8.3]	n.s.
Shoulder	Abd–Add	20.8 (13.0)	25.7 (30.4)	−4.9 [−13.7, 3.9]	n.s.
	Flex–Ext	63.8 (28.3)	37.6 (41.0)	26.2 [17.4, 35.0]	n.s.
	Ext–Int	47.9 (12.3)	25.2 (41.4)	**22.7 [13.9, 31.5]**	**0.016**
Elbow	Abd–Add	54.7 (15.3)	52.3 (45.9)	2.4 [−6.4, 11.2]	n.s.
	Flex–Ext	104.5 (42.3)	80.5 (22.5)	**24.0 [15.2, 32.8]**	**<0.039**
	Ext–Int	61.2 (40.5)	31.7 (7.9)	**29.5 [20.7, 38.3]**	**<0.001**

Data are presented as median (IQR). The statistically significant differences are bolded along the corresponding p-value; when the differences are not statistically significant, the p-value is replaced by n.s. (not significant). Note: Diff = differences between healthy and injured players; p = p-value.

Similarly, in the pass phase (Figure 3), the shoulder internal/external rotation, adduction/abduction, and flex/extension ROMs of healthy players were wider than the injured ones (p = 0.050, p = 0.001, and p = 0.007, respectively). Moreover, healthy players showed a higher elbow flexion peak than the injured ones (p = 0.022) (Table 4). Joint kinematics (minimum and maximum peak angles) and SPM1D analysis of the pass phase are presented in the Supplementary Materials (Figures S4–S6; Table S2).

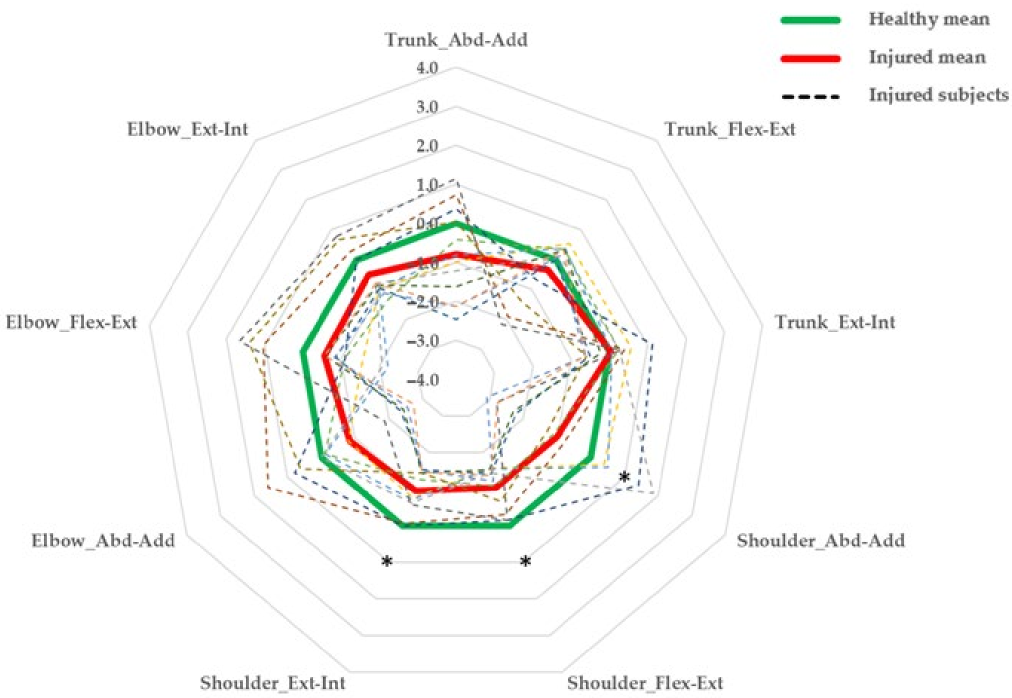

Figure 3. A radar chart of the joint ROM kinematic comparison between healthy and injured players, standardized using Z-scores, during the pass phase. The black line represents the normalized mean ROM of healthy players, while the red line represents the ROM of injured players. Each dashed line corresponds to the ROM of individual injured players. Note: * = p-value < 0.05. Abd–Add: abduction–adduction, Flex–Ext: flexion–extension, Ext–Int: external–internal rotation.

Table 4. ROM parameters extracted for the trunk, shoulder, and elbow during the pass phase for the healthy and injured players.

Pass					
Joint	**Rotation**	**Healthy**	**Injured**	**Diff [95% CI]**	***p***
Trunk	**Abd–Add**	29.3 (11.0)	23.3 (12.4)	6.0 [−26.5, 38.5]	n.s.
	Flex–Ext	30.5 (14.5)	32.5 (11.9)	−2.0 [−38.8, 34.8]	n.s.
	Ext–Int	40.1 (12.3)	40.8 (9.5)	−0.7 [−31.2, 29.8]	n.s.
Shoulder	**Abd–Add**	80.9 (22.3)	58.7 (47.8)	22.2 [−81.2, 125.6]	**0.050**
	Flex–Ext	159.8 (74.6)	74.7 (66.3)	**85.1 [−110.5, 280.7]**	**0.001**
	Ext–Int	152.8 (141.1)	82.6 (70.0)	**70.2 [−238.5, 378.9]**	**0.007**
Elbow	**Abd–Add**	74.8 (21.0)	67.9 (43.5)	6.9 [−87.8, 101.6]	n.s.
	Flex–Ext	151.0 (39.4)	122.0 (44.9)	29.0 [−88.1, 146.1]	n.s.
	Ext–Int	105.3 (109.0)	65.3 (81.8)	40.0 [−227.1, 307.1]	n.s.

Data are presented as median (IQR). The statistically significant differences are bolded along the corresponding p-value; when the differences are not statistically significant, the p-value is replaced by n.s. (not significant). Note: Diff = differences between healthy and injured players; p = p-value.

4. Discussion

The present study aimed to investigate the biomechanical differences between healthy and injured first-division softball players in a common throwing movement performed in an ecological environment by means of wearable inertial sensors.

The most important finding of the present study was that the shoulder-injured players showed a lower ROM in the shoulder, elbow, and trunk joints than the healthy ones during a common throw. These findings suggest that, even after recovery and return to play, athletes may continue to exhibit conservative biomechanical strategies to protect themselves against re-injury or they may display a reduced ROM due to structural impairments or sensations of pain. Considering whether these changes in the ROM are protective adaptations [18] or if they could potentially predispose athletes to other injuries in the future due to compensatory mechanisms [3,16] is crucial for rehabilitation, post-rehabilitation, and training programs.

The kinematic results of the present study show a consistent lower ROM across all joints' movements analyzed, with the exceptions of shoulder abduction–adduction (during the pickup phase), trunk flexion/extension (during the pass phase), and trunk external–internal rotation (during both phases). However, these differences were not statistically significant. In the pass phase, injured players showed a significantly lower ROM in all the shoulder's movements. However, contrary to our expectations, the players did not demonstrate differences in trunk or elbow kinematics, which are typically compensatory movements that can help maintain a high level of performance when throwing [6]. This lack of compensatory activity suggests that the reduced shoulder ROM directly impacts throwing mechanics, potentially hindering the performance rather than adapting to maintain it [28].

Reduced joint ROM can be attributed to several factors, among which pain is notably significant. Pain in the shoulder is a well-recognized factor that can lead to a decreased ROM [29]. However, in this study, softball players did not report experiencing pain in their upper-limb joints before or during the trials, suggesting that the observed biomechanical changes were not influenced by acute discomfort, but may instead reflect other adaptations.

These results may underscore the persistent impact of shoulder injuries on throwing kinematics. Wilk et al. (2002) observed that athletes often exhibit altered shoulder mechanics post-injury, which may not fully return to pre-injury patterns even after perceived recovery. Similarly, Hamer et al. [18] found that high-school and collegiate baseball pitchers who had undergone an ulnar collateral ligament reconstruction showed significantly lower degrees of elbow extension compared to the healthy controls. However, they did not find a reduced ROM in injured baseball pitchers from before to after ulnar collateral ligament reconstruction [18]. This raises the question of whether players exhibiting a reduced ROM might be more susceptible to injuries during a throwing movement, independent from previous injuries.

Shoulder ROM is essential for preventing injuries in athletes, particularly in sports involving overhead movements [3]. A restricted shoulder ROM has been associated with an increased incidence of shoulder injuries [30]. For example, in baseball pitchers, inadequate shoulder external rotation is associated with a higher risk of shoulder injury and the need for surgery [31]. Furthermore, generalized ligamentous laxity has been identified as a predisposing factor for shoulder injuries in athletes, emphasizing the importance of maintaining a proper ROM to prevent such injuries [32].

To the best of our knowledge, this was the first study to investigate the differences between healthy and injured position softball players throw. Most research has traditionally focused on pitchers' pitch [18], given the higher incidence of shoulder injuries in such a population. In absolute terms, non-pitcher softball players reported more upper-limb injuries than pitchers. This is both due to the larger number of position than pitcher players and their huge effort in the throwing movements performed. Therefore, investigating the prevalent injuries among position players represents a critical and slightly unexplored area of concern due to the implications for injury prevention and management.

Krajnik et al. [8] reported that most of the injuries occurred during softball practice rather than during competition, with a notably higher percentage (65%) of injuries happening to position players [8]. This suggests that training environments and routines might expose players to greater risks, possibly due to repetitive drills [8], inadequate recovery times [33], or insufficient attention to proper mechanics during practice [3], as most of the injuries occur due to non-contact and overuse mechanisms. This highlights the critical role of training, as most injuries in position softball players occur in non-contact situations during training. Moreover, the ecologically valid design of the present study, including tests performed by means of wearable inertial sensors in the regular softball training pitch, could have highlighted kinematics compensations otherwise hard to detect in a laboratory environment. It has been shown in previous studies on other sports that context-related elements contribute to highlight differences from controlled laboratory settings [22,34]. The radar chart representation through the Z-score analysis was designed to facilitate the assessment of multiple biomechanical variables with different magnitudes and therefore promote a clinical-friendly interpretation and sharing among clinicians, coaches, and players (or patients) [35].

The present study has several limitations: first, the limited sample size presented by the pilot nature of this study. Despite several biomechanical studies having been performed with 10 subjects or less, a more extensive cohort could have led to a better interpretation of the differences between healthy and injured players in the movements investigated. Second, the rehabilitation protocol, the time from injury, and the recovery time were not controlled and differed among the injured players. However, all players belonged to the same team and the same medical and coaching staff organized their return to sport in the same way after clearance. Third, the sampling frequency of the wearable sensor might have been at the lower bound to produce a proper analysis of such high-speed (high gravity—g) movements [36]. Further investigation of the potential biases due to the technological limitations is mandatory.

5. Conclusions

This study provided novel insights into the biomechanical alterations observed in position softball players following shoulder injuries. A significant lower ROM in the shoulder, elbow, and trunk was found in shoulder-injured players compared to matched healthy controls. Such a reduced ROM is likely a direct consequence of shoulder injuries. Despite this, players all returned to play and reported no residual pain. Reduced ROM in the shoulder complex can also serve as a potential risk factor for subsequent shoulder injuries. Ecologically valid biomechanical studies by means of wearable inertial sensors could help highlight residual compensations and injury risk for softball players and help objectify return-to-sport clearance criteria.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15041941/s1, Table S1: Peaks and ROM parameters extracted for the trunk, shoulder, and elbow during the pick-up phase for the healthy and injured players; Table S2: Peak parameters extracted for the trunk, shoulder, and elbow during the pass phase for the healthy and injured players; Figure S1: Trunk kinematic comparison between healthy and injured players during the pick-up phase; Figure S2: Shoulder kinematic comparison between healthy and injured players during the pick-up phase; Figure S3: Shoulder kinematic comparison between healthy and injured players during the pick-up phase; Figure S4: Trunk kinematic comparison between healthy and injured players during the pass phase; Figure S5: Shoulder kinematic comparison between healthy and injured players during the pass phase; Figure S6: Elbow kinematic comparison between healthy and injured players during the pass phase.

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Informed Consent Statement: Informed consent was obtained from each player's parent/tutor involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article and Supplementary Materials. Further inquiries can be directed to the corresponding authors.

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