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Test-retest reliability of customised inertial measurement units (IMUs) in evaluating skateboarding related manoeuvres

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Abstract

Recent developments in sports technology have enabled sports engineers to utilise the availability of inertial measurement units (IMUs) to develop a customised system for data collection during sports performances. Ensuring the reliability of such a system is essential for objective data collection and transmission of information that coaches could rely upon for improving athletes' techniques and overall performance. The aim of this study was to investigate the reliability of a custom-made IMU system (embedded with Arduino Pro Mini) in the evaluation of skateboarding related manoeuvres. A skilful male and experienced amateur skateboarder (23 years, with 5 years skateboarding experience) performed five skateboarding tricks (Ollie, Nollie, Pop Shuvit, Kickflip and Frontside 180) using a customised ORY skateboard (IMUs fused). The skateboarder was permitted to execute two separate tricks (Tests A and B); thereafter, the reliability of the IMUs in recognising the similarity of the tricks was evaluated using a test-retest approach. Six time-domain signals obtained from the IMU system of each trick's execution were extracted. Statistical analyses, including the Kolmogorov-Smirnov test, intraclass correlation coefficients (ICC), Cronbach alpha and correlation coefficients, were utilised to measure the scale's reliability of the system. The results revealed no significant difference between Tests A and B of each trick $p > 0.05$, ICC > 0.80, Cronbach alpha > 0.80 and $r > 0.80$; p-value < 0.001. A relatively lower root means square error and mean absolute error were obtained, further suggesting the effectiveness of the system in detecting the similarities in the movement patterns of the skateboarder during the trick execution. The IMU system appeared to be reliable in measuring skateboarding tricks performances. The present findings could serve as guidelines for testing future, custom-made, IMU devices before the commencement of data collection.

Keywords

Skateboard, inertial measurement unit, reliability, trick manoeuvres, test-retest

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Introduction

The acronym IMU refers to an inertial measurement unit, which is a microelectromechanical device that comprises accelerometers and gyroscopes. The device serves as a means to evaluate, measure and track records of any specific force, movement, angular degree and the orientation of the human body.[1] The sports industry has leveraged the advent of technologies where sports engineers have made use of the accessibility of customising IMUs to establish a bespoke system to acquire information during sports performances. This development, coupled with the growing interest in

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developing personalised applications, has triggered the employment of cost-effective means of data acquisition in many fields, including the sports and exercise domain.

Many researchers have employed IMUs for monitoring movements due to their cost-effectiveness and the provision of realistic values to the users.[2–5] Further advantages of utilising an IMU over the other laboratory-based conventional systems are attributable to its compact dimension, flexibility, manageability and simple installation.[6] Moreover, IMUs can be used to evaluate human-related activities and movements without any restrictions. Indeed, IMUs could support data collection both on and off the field as opposed to the conventional system in which the data collection is largely confined to laboratory settings. The IMUs are efficient in collecting and transmitting data, as the sensors within the system can be synchronised with various external devices, such as smartphones, computers and other cloud-related systems.[7] Thus, IMUs have the potential to quantify human activity and movement to support the provision of feedback concerning specific activity types and movements.

Skateboarding is considered a self-expression and action sport in which a skater uses a small board mounted on wheels to perform tricks by manoeuvring the board to execute several types of movements. The popularity of the sport among youths of age between 15 and 24 years has recently proliferated, prompting its debut at the 2020 Tokyo Summer Olympics.[8] This development led to the conduct of several different studies in understanding and classifying movement patterns through the application of customised IMUs and machine learning analysis. In this regard, Abdullah et al.[9] used the integration of IMU to classify skateboarding manoeuvres, where the data derived from the IMU device was classified using a machine learning model, yielding an accuracy of 95%. Ibrahim et al.[10] also investigated the classification of skateboarding manoeuvres, albeit using a different machine learning model that is, *k*-Nearest Neighbour (*k*-NN), with the application of customised IMU. The authors reported 85% classification accuracy. Moreover, Shapiee et al.[11] utilised the customised IMUs in determining the class of skateboarding tricks via an image processing method and machine learning algorithms, resulting in a classification accuracy of 99.5%. The overall findings of the previous investigations demonstrated that customised IMUs could potentially serve as a medium of data collection for studying movement patterns, as well as classification of manoeuvres in skateboarding, which has the potential to be practically useful in supporting judges in objectively evaluating trick performance, as opposed to the subjective and conventional techniques currently applied.

Although IMU devices appear to be useful as a medium for data collection in skateboarding sport, as shown in earlier studies,[9–11] nonetheless, the establishment of the reliability of the device itself, especially in the skateboarding field, is still in its' infancy. Indeed, a recent case report indicated that most performance analysts rarely report the reliability of their analysis, presuming that the presence of performance indicators could manifest the reliability of their analysis.[12]

Skateboarding is a unique sport that involves several movements, ranging from braking, gliding, skidding, as well as sliding while maintaining speed. Thus, classifying the data obtained from the IMU sensors is likely inadequate to guarantee the reliability of the movement patterns. Consequently, the current study sought to conduct reliability tests of a customised IMU system for measuring skateboarding manoeuvres. Reliability of a sensor pertains to the sensor producing a relatively consistent value upon repeated usage.[13] It should be noted that before the application of any IMU system, it is vital for the device to be reliable to provide objective data collection and the transmission of reliable information, that, consequently, could be practically implemented by coaches, athletes and judges.

Methodology

Participants

A healthy, skilful and experienced male amateur skateboarder (23 years of age, with ~5 years of skateboarding experience) with a normal body mass index (BMI) was recruited to perform the required skateboarding manoeuvres, namely, the Ollie, Kickflip, Pop Shuvit, Nollie and Frontside 180 in the current investigation. The aforesaid skateboarder was purposely chosen due to his capability to execute the skills seamlessly as well as provide a similar pattern of performance in repeated actions. For a detailed description of each trick manoeuvre, readers can refer to the article by Shapiee et al.[11]

Instrumentation of IMU device

The IMU system was modelled by using CATIA software (Figures 1 and 2). It comprises an IMU, with product code SN-IMU5D-LC, Arduino Pro Mini, a Bluetooth module and a 3.7 V Lithium Polymer rechargeable battery. The instrumented system samples a certain skateboarding trick at 20 Hz for 3 s, producing six channels of skateboarding tricks' signals, containing 60 sampling points. A Zortax M200 Plus 3D printer was employed to build a suitable casing for the device such that it does not impede the movement of the skateboard throughout the tricks' execution. All apparatus, along with the microcontroller system, utilised in the current study have been documented in earlier research.[14]

Data acquisition

The skateboarder was directed to perform two separate manoeuvres (Referred to as tests A and B). The

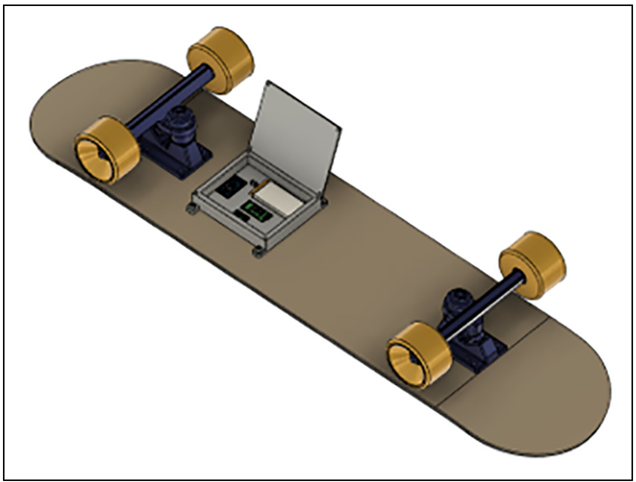

Figure 1. ORY skateboard with customised IMU instrumentation.

skateboarder was encouraged to produce similar movement patterns owing to his skill level as an experienced skateboarder. The first test was initially conducted (Test A) and then after a rest interval of about 30 min, another test was carried out (Test B).[15] This was deemed necessary to test the efficacy of the sensors at varying times. It was postulated that the fusion sensors could move in tandem with the movement of the skateboarder.

Both Test A and B were carried out three times by the skateboarder, equating to a total of 30 tricks executed, 15 tricks in Test A and 15 tricks in Test B. All the tests were carried out by the same skateboarder, using the same equipment and under relatively similar conditions. The data comprising the acceleration and angular velocity of the motions were collected in real-time. The accelerometer measures acceleration with a minimum full-scale range of ± 3 g where the X, Y and Z-axes, are denoted as aX, aY and aZ, respectively. Conversely, the gyroscope measures the corresponding rotational speed (°/s), along the three aforesaid axes, denoted as ωX, ωY and ωZ, respectively.

For the data pre-processing, all six signals retrieved from the corresponding accelerometer and gyroscope data within the trick execution window were used to identify a particular trick. Thus, a mean value was taken individually from each axis of both the accelerometer and gyroscope data that is, $Mean_{ax}$, $Mean_{ay}$, $Mean_{az}$ and $Mean_{gx}$, $Mean_{gy}$, $Mean_{gz}$, depicting one skateboarding trick.[16,17] These features of three trials were taken in each test (Test A and Test B) and the best for each was utilised for statistical analysis.[18] The best amongst the three trials was determined when the skater executed the tricks and properly landed on the board. It is important to highlight that before the commencement of the study informed consent was obtained from the skater and ethical approval was received from the university human research ethic committee (UMT/JKEPHMK/2021/53).

Statistical analysis

Data analysis was completed via multiple statistical analyses using XLSTAT version 2021.2.2 for Microsoft Windows and Statistical Package for the Social Sciences (SPPS version 26 for Windows). To test the reliability of the IMU device, a series of reliability tests were conducted, including the Kolmogorov-Smirnov test, intraclass correlation coefficient (ICC) and Cronbach's alpha analysis. Moreover, a Pearson correlation analysis was implemented to test the relationship between the movement patterns carried out by the skateboarder. Meanwhile, the ICC, Kolmogorov-Smirnov, as well as Cronbach's alpha, were used to determine the reliability of the sensors.[19,20] Root Mean Square Error (RMSE), coupled with Mean Absolute Error (MAE), were also utilised to study the variations of the movements executed by the skater in the current investigation.

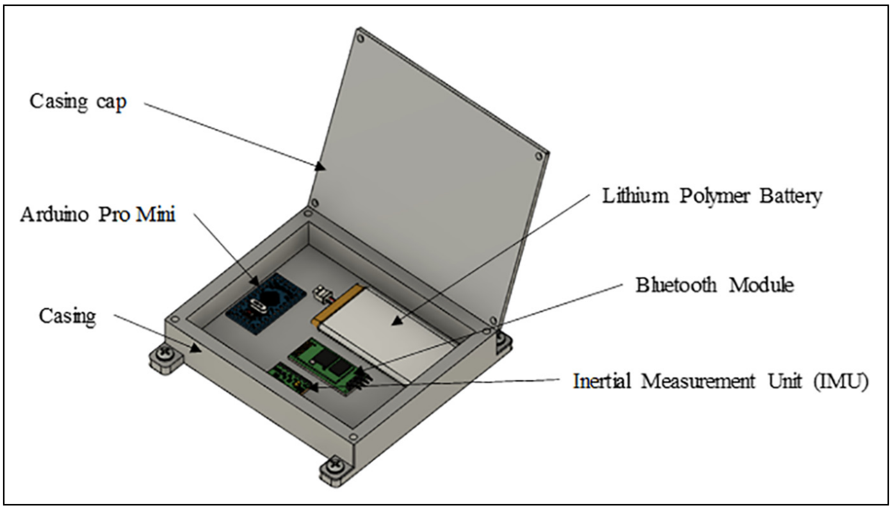

Figure 2. Instrumentation of IMU device.

Table 1. Inferential statistics of Kolmogorov-Smirnov test.

Test re-test	Observation	D	p-Value
Ollie	Test A Test B	0.275	0.097
Nollie	Test A Test B	0.200	0.400
Pop Shuvit	Test A Test B	0.200	0.400
Kickflip	Test A Test B	0.125	0.913
Frontside 180	Test A Test B	0.125	1.000

Results

Kolmogorov-Smirnov analysis

Table 1 presents the inferential statistics of the Kolmogorov-Smirnov test. Accordingly, no statistically significant differences were observed across all manoeuvres in Tests A and B, $p > 0.05$. This implies that the fusion sensors were able to recognise the similarities of the movement patterns executed by the skateboarder. Moreover, Figure 3 shows the cumulative distributions of each skateboarding trick analysed via the Kolmogorov-Smirnov test.

Intraclass correlation coefficient (ICC) and Cronbach's alpha analysis

Table 2 details the results of ICC and Cronbach's alpha coefficients obtained from the test re-test of skateboarding tricks execution. Higher coefficient values for both the ICC and Cronbach's alpha, ranging from 0.81 to 1, were obtained for the test re-test across all five tricks in both Test A and B. This suggests the high reliability of the IMU device. Similarly, the analysis of the variation in the movement patterns executed by the skater is depicted by the RMSE and MAE coefficients. Accordingly, RMSE values for the Ollie and Pop Shuvit were higher as compared to the other tricks, which could be attributed to the difficulty level associated with the skills. However, lower MAE coefficients were observed, which could reflect the ability of the skater in replicating the tricks with relatively fewer variations.

Pearson correlation analysis

Table 3 shows the correlation matrix between all the tricks in both Test A and B. Positive and strong Pearson correlation coefficients were detected from all the tests (Ollie $r = 0.703$; $p < 0.001$, Nollie $r = 0.892$; $p < 0.001$, Pop Shuvit $r = 0.674$; $p < 0.001$, Kickflip $r = 0.890$; $p < 0.001$, as well as FS180 $r = 1.000$; $p < 0.001$). Likewise, Figure 4 illustrates the scatter plots for each tricks' test re-tests.

Discussion

The purpose of the current study was to evaluate the reliability of a customised IMU system for the measurement of skateboarding tricks execution. The data collected using the IMU device was subjected to a series of reliability tests, with a view to ascertaining its effectiveness as a monitoring device for generating and transmitting reliable information. It was shown from the series of reliability analyses carried out that the sensors were reliable for measuring skateboarding related manoeuvres.

The Kolmogorov-Smirnov analysis revealed no statistically significant difference between Test A and Test B, as demonstrated in Table 1. The reliability of the sensor was evident in the relatively equivalent results over repeated measurements that is, test re-tests. Similarly, all of the test re-tests exhibited similar distributions, supporting that there were no significant differences across repeated measurements between the two tests, as shown in Figure 4, which is unsurprising given the experience and skill level of the recruited skateboarder. Moreover, this finding is concordant with the results of a previous investigation which demonstrated the effectiveness of the Kolmogorov-Smirnov test in predicting the reliability of locally developed archery chronometer sensors in test-retest evaluations.[21] Moreover, a similar approach was advocated by researchers investigating the reliability of customised IMU sensors in evaluating and discriminating two different types of movements executed by an archer.[22,23]

ICC analysis, with a two-way mixed model, and absolute agreement types, along with a 95% confidence interval, were used in this study. Additionally, Cronbach's alpha analysis was employed to concurrently verify the internal consistency of the data retrieved from the IMU sensors. Good to excellent coefficient values for both the ICC and Cronbach's alpha, ranging from 0.81 to 1, were obtained in the current investigation, as shown in Table 2. The ICC and Cronbach's alpha has been previously reported as suitable methods of testing data reliability,[24,25] where an ICC coefficient value $\geqslant 0.80$ indicates a relatively good to excellent reliability.[26] Similarly, the Cronbach's alpha coefficient values observed in this study suggest good consistency of the data gathered from the sensors. This result is correspondent with that of previous researchers who investigated the internal consistency of IMU sensors and found the IMUs were effective in evaluating lower limb related sporting activity.[27,28] Consequently, the high value of the coefficients observed in the current study could reflect the reliability of the IMUs utilised in measuring the tricks performed.[29]

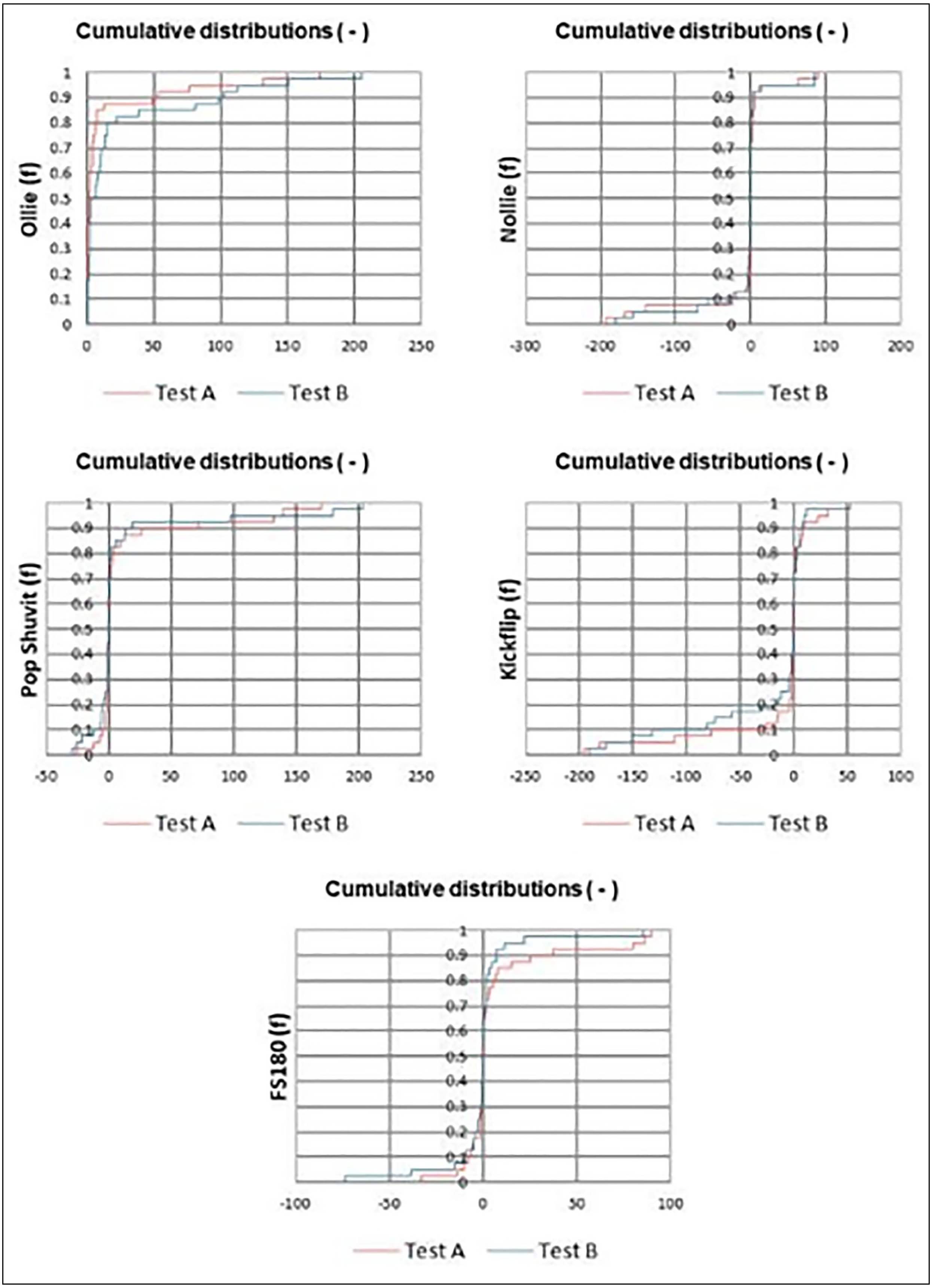

Figure 3. Kolmogorov-Smirnov test for the tricks executed.

Table 2. Intraclass correlation coefficient (ICC) and Cronbach's alpha coefficients in reliability test.

Test re-test	Observations	95% Confidence interval			
		ICC	Cronbach's alpha	RMSE	MAE
Ollie	Test A Test B	0.811	0.811	33.891	12.862
Nollie	Test A Test B	0.936	0.94	23.461	10.762
Pop Shuvit	Test A Test B	0.806	0.802	35.43	14.731
Kickflip	Test A Test B	0.941	0.94	19.682	8.592
Frontside 180	Test A Test B	1	1	22.061	9.431

Table 3. Pearson correlation matrix.

Variables	1	2	3	4	5	6	7	8	9	10
1. Ollie A	1									
2. Ollie B	**(0.703)**	1								
3. Nollie A	0.815	0.861	1							
4. Nollie B	0.705	0.667	**(0.892)**	1						
5. Pop Shuvit A	0.685	0.503	0.638	0.576	1					
6. Pop Shuvit B	0.795	0.571	0.661	0.514	**(0.674)**	1				
7. Kickflip A	−0.032	−0.084	−0.022	−0.065	−0.001	−0.048	1			
8. Kickflip B	−0.076	−0.108	−0.066	−0.084	0.064	−0.105	**(0.890)**	1		
9. FS180 A	0.032	−0.066	0.049	0.001	−0.089	0.032	0.555	0.559	1	
10. FS180 B	0.032	−0.066	0.049	0.001	−0.089	0.032	0.555	0.559	**(1.000)**	1

Values in bold are different from zero with a significance level alpha = 0.05 (95% Confidence interval).

The RMSE and MAE coefficients analysis were used to discern the variability of the movement patterns executed by the skater.[30] The RMSE values for the Ollie and Pop Shuvit were found to be higher as compared to the other tricks (Table 3). This could be explained by the complex and multifaceted nature of the two tricks; for instance, a Nollie trick has been reported as a complex manoeuvre that requires coordinated actions of jumping and movement to bring both the skater and the board into a vertical and horizontal position.[31] A recent study has also described the Pop Shuvit trick as a complex manoeuvre in which the skater is required to flick the back foot down while the front foot remains in place allowing the board to spin in 360° in the air with no further flips.[32] Thus, the difficulty level associated with the Nollie and Pop Shuvit skills, as opposed to the other skills examined, could explain the higher RMSE values obtained in the study. However, the relatively lower MAE coefficients observed may reflect the ability of the skater in replicating the tricks with comparatively fewer variations.

In the present study, positive significant linear relationships were observed between the tricks (Ollie A and B, Nollie A and B, Pop Shuvit A and B, Kickflip A and B as well as FS180 A and B; Table 3). Moreover, the scatter plots, shown in Figure 4, corroborated the strength and directionality of the relationship among the tricks, which further emphasised the associations between the test re-tests criterion. This finding agrees with previous work, where it was reported that IMU sensors could be deemed reliable when they produce comparable results across repeated measurements, using a similar protocol.[33–35]

Conclusion

The present study assessed the reliability and validity of a custom-made IMU device in measuring skateboarding tricks namely Ollie, Nollie, Kickflip, Pop Shuvit and Frontside 180. Accordingly, the IMU system appeared to be reliable in measuring skateboarding trick performances. The present findings could serve as guidelines for testing future, custom-made, IMU devices before the commencement of data collection.

Practical implications

The uniqueness of the Skateboarding sport as means of self-expression, transportation, recreation, as well as competition, turns out to be especially appealing and popular among youths of 15–24 years. It is envisioned that the popularity of the sport will continue to grow owing to its recent introduction to the Olympic games. For better performance and attainment of success in

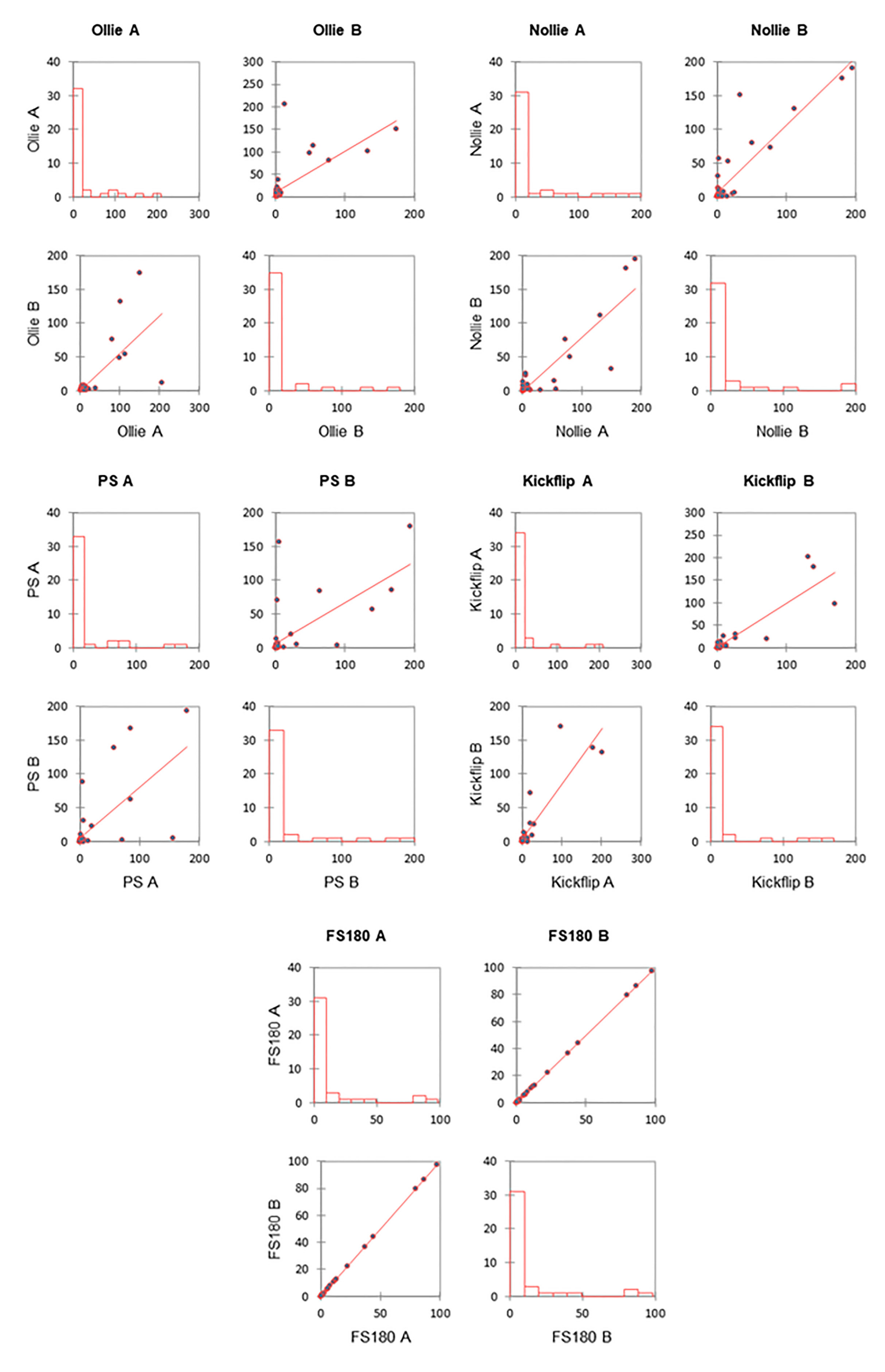

Figure 4. Scatter plots of the tricks executed.

this sport, a skateboarder is required to produce consistent movement patterns to enable the execution of a good trick manoeuvre. The IMU sensors developed and tested in the current study could serve as a potential means of examining the movement patterns of the skaters, which could aid coaches and judges in the objective determination of trick related manoeuvres in real-time, identify inconsistencies and contribute to an unbiased judgement. Moreover, the methodological approaches utilised in this study could be used as guidelines when developing custom-made IMUs devices to ensure the reliability of the device before the commencement of data collection.

Limitations of the study

We were unable to examine the validity of the IMU sensors developed. Future studies could compare the validity of custom-made IMU sensors against other commercially available sensors. However, it is expected that the fusion sensors could move in tandem with the movement of the skater, examining the independent movement of the IMU sensors is beyond the scope of the current investigation. Moreover, due to human biological variability, the precise movement of the skateboarder is not able to be completely accounted for.

Declaration of conflicting interests

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