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REGISTER OF ANKLE ANGLE KINEMATICS DATA USING FUNCTIONAL DATA ANALYSIS FOR PARACHUTE LANDING

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Abstract

The biomechanical data encountered a significant and common difficulty related to event-time alignment due to the fact that each motion capture (MoCap) trial exhibited varying durations to complete the tasks involved. To address this challenge, registration, which is essential for Functional Data Analysis (FDA), needed to be further examined in detail. The primary goal of this study was to evaluate the effectiveness of using both landmark and continuous registration methods on ankle angle data collected during the parachute landing fall activity. In total, twenty-one Malaysian forces participated in this experiment, which included three professional parachutists and eighteen amateurs. Their movements were recorded through two Go-Pro Hero 4 cameras, and the Quintic Biomechanics Software v26 was employed to extract the ankle angle data. The process of registration could be carried out in two distinct ways: by utilizing landmark points and through continuous registration. Landmark registration was performed initially, followed by continuous registration as an additional technique aimed at enhancing the alignment of the curves. Notably, the effectiveness of the registration process was assessed using the Root Mean Square Error (RMSE) test, which revealed that the ankle angle curves were aligned with considerable effectiveness when applying the landmark registration in conjunction with the continuous registration technique. The results yielded minimal RMSE values for both amateur and professional categories, recorded at 8.359 and 9.642, respectively. Moreover, the implementation of these registration techniques notably improved the accuracy of the average measurements for ankle angles.

1. Introduction

Discrete measurements, such as the maximum and minimum peak values of curves or oscillations of several attempts from several persons, are commonly employed to examine biomechanical data [1-3]. Unfortunately, these conventional techniques exclude important curve aspects that must be considered for more precise analysis. Thus, Functional Data Analysis (FDA) is employed to overcome this issue since it analyses all curves as sets of functions instead of discrete measurements, allowing for the assessment of how all curve behaviors change continuously over time [4].

There are various ways used in the curve registration procedure in addition to the FDA method. The Bayesian hierarchical model method, among others, has been applied [5] for the curve registration process for individual growth velocity data. Moreover, Zhang and Parnell [6] applied a shape invariant to perform curve registration clustering method. The shape invariant model uses the spline-B function as the basic function to coordinate the desired curve points. Pataky et al. [7] implemented a curve registration technique for walking activities, and the study's findings demonstrated that the procedure improved the average of the generated data.

The FDA recognizes two distinct registration types: continuous registration and landmark registration. The simplest method for aligning curves is known as landmark registration. This technique involves aligning distinctive features or landmarks so that their placements are consistent throughout all curves. A fair comparison of the curves is made possible by aligning all the landmarks selected for the curves at different time points to the same time point. These distinguishing features, also known as landmarks, are maxima, minima, or zero-crossings of curves [4]. Furthermore, landmark registration might not always be suitable for all kinds of data since certain curves lack equivalent curve properties or landmarks, and because some landmarks are ambiguous for other curves. Certain variations may go undetectable while aligning the curve at a single landmark point. Therefore, an additional method has been applied with continuous registration for improved curve alignment. In contrast, continuous registration obtains a more precise curve alignment by using entire curves as opposed to identifying the values of certain features or landmarks. Regardless of how simple or complex the work of finding landmarks is, figuring out the durations of chosen landmarks requires tedious graphical procedures [8].

Researchers interested in reviewing research data, particularly those working in the subject of biomechanics, have taken an interest in the FDA technique created by [4]. There are several researchers who have solved the problem of curve alignment using landmark registration; for example, [9] applied this method to sit-stand exercise. Moreover, [10] utilized landmark and continuous registration for upper extremity angle data of the Malaysia military during a shooting activity. In [11] biomechanics data has been considered for planting palm oil. References [12-15] considered registration align curve for kinematics and kinetics data for parachute landing activity, while [16] considered cycle of America's kettlebell swing. Several other researchers have registered data for a variety of activities using the FDA approach [17-23]. Motivated by these previous studies, this work evaluates the extent to which landmark registration and continuous registration, either in addition to or instead of landmark registration in the FDA, reduce the inter- and intra-subject phase variability of ankle angle data collected during Parachute Landing Fall (PLF) operations.

2. Research Methods

2.1. Experimental and data collection

Three parachutists who were professionals (age: 28 ± 1.73 years; height: 1.67 ± 0.02 m; weight: 65.3 ± 7.62 kg) and eighteen amateurs (age: 23.8 ± 2.11 years; height: 1.69 ± 0.05 m; weight: 62.9 ± 5.93 kg) were recruited to participate in this experiment. Authorised by the Commander of the Headquarters of Malaysian Army, the experiment was conducted at the Training Static Parachute Landing facility for Malaysian Army in Kem

Sungai Udang, Malacca. After receiving a briefing on the test methods, each participant signed a written consent form. To obtain ankle angle data, two Go-Pro Hero 4 cameras were used, each capable of capturing 60 frames per second at a very high-quality of 1080 pixels.

Each subject wore military outfit camouflage gear during training and testing. They all wore identical parachuting boots and helmets. During the landing exercise, each participant wore a 10-kilogram weight bag affixed to their front bodies. To swing like a pendulum, the first subject will grab an iron swing and ask a second amateur to help push him. Next, the subject would let go of the iron swing and fall on a mattress that was one centimeter thick by using the Parachute Landing Technique (PLF). Each subject will land three times to obtain more accurate ankle angle data, as shown in Figure 1. When the person releases the grip of the iron swing and strikes with their foot, the ankle angle data starts to be collected. When both feet touch the ground, the foot striking location is recorded. Quintic Biomechanics software version 26 was used to digitise the data and present the ankle angle results in Microsoft Excel.

Figure 1. The position of participant by applying PLF technique.

2.2. Curve registration using functional data analysis

The registration method is applied in FDA to solve the variation problem that occurs in the time phase and amplitude for each curve studied. The registration method applied in this study is curve registration. The purpose of this curve's registration is to align curves, such as the maximum or minimum point of data, in terms of their shape. The curve registration method can be used to modify amplitude changes in the curve that occur on the axis. Ankle angle data during parachute landing activities are studied using curve registration. This approach is based on the shape's visual characteristics, such as the intersection point, minimum point, and maximum point, which are determined by the derivative function. Using work in [4] as a guide, some of the actions needed to align the curve with the maximum or minimum point for the purpose of amplitude comparison are as follows:

(a) Identify the maximum or minimum x_j value from each curve that needs to be changed.

(b) Construct a transformation known as a warp function h_j for each curve. The value $x_j^*(t)$ depicts the following displacement curve

$$x_j^*(t) = x_j[h_j(t)]. \tag{1}$$

(c) The warping function developed for each curve is to place the curve in the designated place as in Step 1.

(d) Estimate the inverse function of the warp h^{-1} by plotting the value of the alignment function against the curve as follows:

$$h^{-1}[h(t)] = t. \tag{2}$$

Professional and amateur ankle data must all be smoothed [24] and recorded utilising the FDA technique. The final analysis of the study is based on the average value of the data following the registration process.

2.2.1. Landmark registration is the simplest curve alignment. A feature that has a location that is easily recognised in every curve is called a landmark [8]. Landmarks can be found at minima, maxima, or zero crossings; each curve has three of these landmarks. The commands use Software R's or Matlab's landmarkreg function to achieve landmark registration.

2.2.2. Continuous registration has been applied in this study as an additional technique to improve curve alignment. This method used the least eigenvalue across the components of the curve [8]. If the curves are multivariate, like the coordinates of a moving point, then the goal is to minimize the sum of the smallest eigenvalues of the curve vector components. The commands use Software R's or Matlab's register.fd function to perform continuous registration.

$$C(h) = \begin{bmatrix} \int \{x_0(t)\}^2 dt & \int x_0(t)x[h(t)]dt \\ \int x_0(t)x[h(t)]dt & \int \{x_0[h(t)]\}^2 dt \end{bmatrix}. \tag{3}$$

2.2.3. Root mean square error (RMSE) is part of evaluation used to determine the best measurement of curve registration. The smallest value of RMSE produced was indicated the best method used. The formula of RMSE is as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (predicted_i - actual_i)^2}{N}} \tag{4}$$

which is a measure of the differences between the predicted value and actual observed or value.

3. Result and Discussion

The registration process applied in this study is to standardize the data and align the curve according to the maximum point and the minimum point. Previous studies have used the time percentage method to align curves [25]. However, this method has produced a shrivelled or inflated curve that did not resemble the original curve of the study. Therefore, the selection of the FDA method to solve the curve alignment problem is the most systematic and effective way. The ankle angle data for each parachutist must first be smoothed before the registration process is implemented. The techniques can be referred to Gunning et al. [24], and the FDA's smoothing procedure was followed. Two registration techniques are employed in this study: continuous registration and landmark registration.

The first step is to determine which point must be modified. During the registration process, each value of ankle angle data was stored as a matrix and was adjusted based on the maximum or minimum point. Figure 2 indicates the maximum or minimum point to be modified. There are numerous dotted lines put on the graph, as illustrated in Figure 2. This dotted line represents the foot strike event for each parachutist at different times. Therefore, to align the event point (maximum point) with one that was set at the same time position, the registration technique was performed.

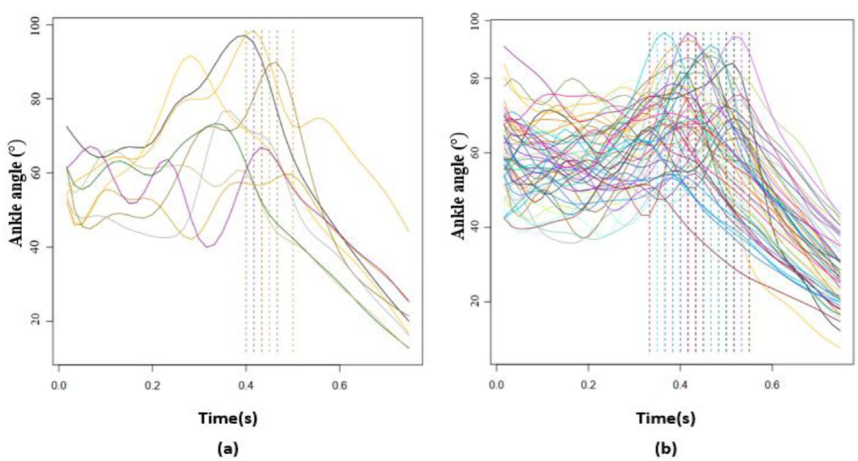

Figure 2. Phase points of ankle angle are identified for alignment (a) professionals (b) amateurs.

Once the maximum or minimum point has been determined, the process of landmark registration and continuous registration is applied to professional and amateur parachutists' ankle angle data. Upon applying the landmark locator to the designated peak of the curve, it is observed that all amplitudes exhibit a decrease in phase variability, as depicted in Figure 3 and Figure 4 depicts the post-registration procedure using four graph sketchers. The ankle data of the parachutists prior to registration is shown in Figure 3(a) and Figure 4(a). Since each parachutist falls at a different time, the graph shows the maximum point at various times. Meanwhile Figure 3(b) and Figure 4(b) describe the ankle angle data after application of landmark registration. The graph indicates that the maximum point seems to move to a specific point in time, but it is still not very well linked together.

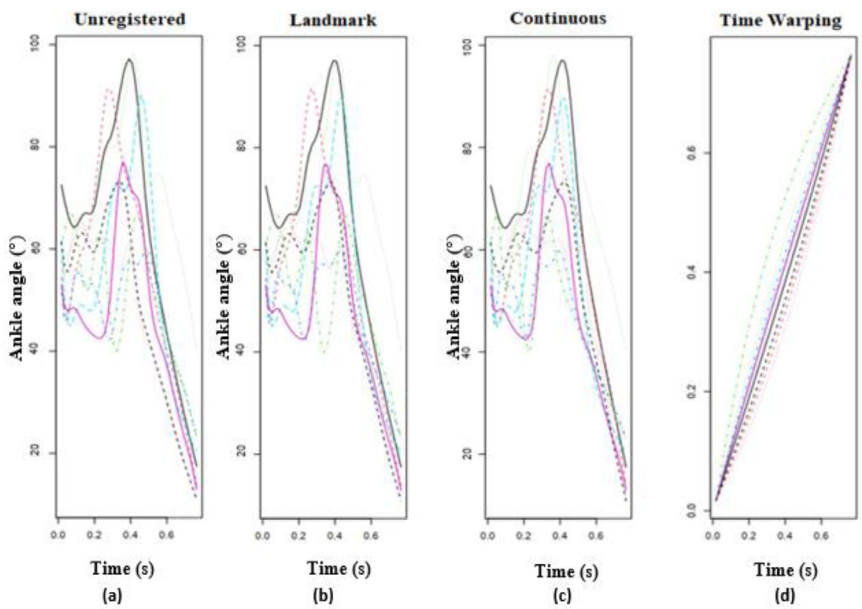

Figure 3. Ankle angle for professionals (a) before registration, (b) after applying landmark registration, (c) after applying landmark and continuous registration and (d) time warping.

The procedure will now move forward with continuous registration, as illustrated in Figure 3(c) and Figure 4(c). Following the application of continuous registration, the curve has been fitted and shaped in accordance with the number of locator settings. Through the estimation of time-warping functions, the phase variation in joint angle curves was eliminated. The adoption of continuous registration was employed to improve the alignment of curves that exhibit an inferior level of alignment through the application of landmark registration techniques. This technique gives the best solution to the curve so that the phase variability in terms of amplitude can be reduced according to Zin et al. [16]. The final graph in Figure 3(d) and Figure 4(d) depicts the time warping. Time warping functions serve as a visual representation of the transformation of the constantly registered curves' time to match the chosen landmark. According to Zin et al. [16], the optimum method for equalising curve points is the landmark and continuous registration process.

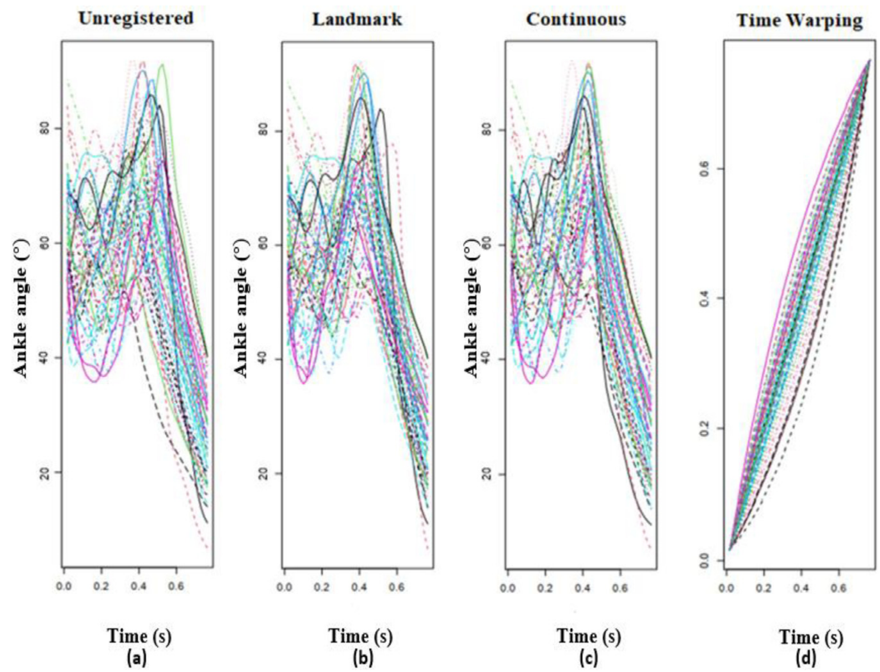

Figure 4. Ankle angle for amateurs (a) before registration, (b) after applying landmark registration, (c) after applying for landmark and continuous registration and (d) time warping.

In this study, each subject is required to perform three parachute landing jumps. The probability of each subject landing at the same time is impossible. Therefore, this landmark and continuous registration technique is applied to gather ankle angle data when the foot touching the ground surface (foot strike) for each subject at the same time. Referring to Figure 3(c) and

Figure 4(c), the maximum point, which is the reading of the ankle angle data when the foot strikes, has been successfully gathered at the same time, which is approximate to 0.4 seconds. Hence, it can produce average ankle angle data when the foot strikes that more accurately represents each group of parachutists, as shown in Figure 5.

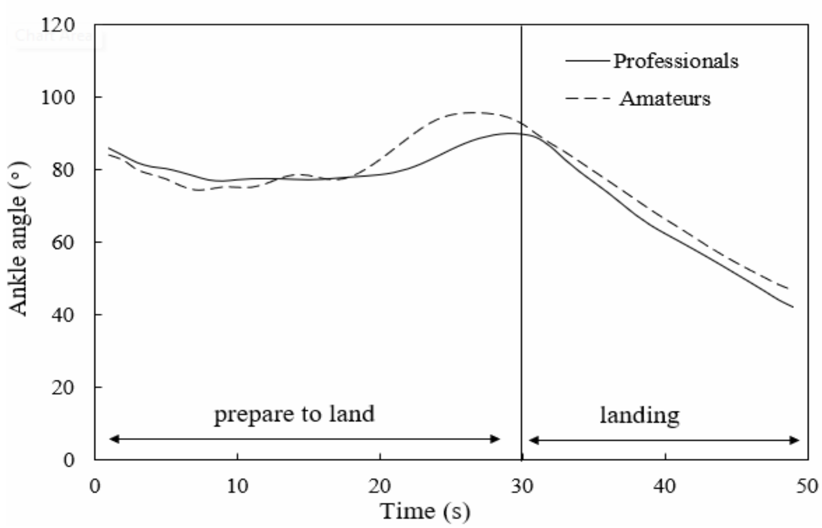

Figure 5. Average of ankle angle for professionals and amateurs after process of registration.

The RMSE test was used to demonstrate that the registration process is improved after using landmark registration in addition to continuous registration. The result shows that the landmark registration with additional continuous registration data yielded the smallest root mean square error (RMSE) values for both amateur and professional categories, which were 8.359 and 9.642, respectively. These values were compared to the RMSE values obtained via landmark registration and the raw data itself. This suggests that continuous registration yielded more accurate measurements compared to landmark registration and raw data. Therefore, the landmark and continuous registration improve the alignment and quality of the average ankle angle data during the foot strike as presented in Table 1.

Table 1. Root mean square error (RMSE) value that indicates registration data comparison

Type of registration	Subject Category	Mean RMSE
Raw	Professional	11.899
	Amateur	10.544
Landmark	Professional	10.483
	Amateur	9.186
Landmark and Continuous	Professional	9.642
	Amateur	8.359

The ankle joint has the highest rate of injury during jump landing activities because it is the first joint to touch the ground after landing [26]. The position of the foot plays an important role during the landing preparation phase because it determines whether the landing is done with the toe first or with the entire surface of the foot. Landing with every part of the foot increases the risk of anterior cruciate ligament (ACL) injury due to the high ground response force [27]. On the other hand, landing on your toes first gives your knee and plantar muscles more time to fully flex your leg as you land on the ground, which can lessen the activation of your quadriceps muscles [28-30]. Referring to Figure 5, it has been shown that the professional parachutist foot strike angle is smaller than that of the amateur. This movement indicates dorsiflexion in the ankle joint. The movement of dorsiflexion in the ankle joint during the landing phase can reduce the ground reaction force and, at the same time, reduce the risk of injury, especially to the metatarsal bones [31].

The primary goal of the registration procedure is to coordinate particular curve shapes, such as the maximum or minimum point of a dataset. This study utilises two different registration methods: landmark registration and continuous registration. Landmark registration changes the curve depending on a preset maximum or minimum point, whereas continuous registration uses nearly all curve points in the data. This study uses both methods for curve registration, and the findings suggest that the curve points can be more evenly distributed. FDA registration has successfully matched curve points based on predefined maximum and minimum points, which was previously impossible. As a result, the FDA approach is the most appropriate for analysing biomechanical data.

4. Conclusion

This work addresses the registration of kinematics data using the landmark and continuous FDA approaches. The RMSE results indicate that the registration procedure is improved by implementing landmark registration and continuous registration. As each of the subjects landed at a different moment, the peak ankle angle was variable. By combining landmark and continuous registration, the ankle angle data during the foot strike (maximum points) can be relocated and gathered at a single point in time, which is 0.4 seconds. This registration procedure increases the accuracy of average ankle angle measurements. In addition, the ankle angle data obtained from professional parachutists can be utilised as a reference source for amateur parachutists to improve their landings and reduce the risk of injury. Furthermore, the findings of this study can be utilised as a reference for parachute sports, not just military applications.

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