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Turning the Tables on Analysing Turns – Validation of Wearable Sensors in Ballet

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Abstract

Introduction: Wearable technology continues to be a growing area of interest to sports scientists and researchers. At the same time, wearable technology appears to have had little impact on the performing arts, specifically dance and classical ballet (ballet). Ballet dancers have the athletic capabilities of sportspeople, with the physical demands and performance levels of their occupation often as high as elite sports. Therefore, coupled with the gap in the literature about wearable technology, specifically wearable sensors, in ballet, there exists a need to determine whether wearable technology can be applied in the performing arts environment.

Aim: The aim of this research was to validate and determine the levels of agreement in timing between a wearable sensor and three-dimensional motion capture camera system when dancers perform a pirouette en dehors from 4th position.

Methods: Nine dancers from the Australian Ballet School participated in the study. Each participant performed nine pirouettes in total: three single, three double, and three triple pirouettes en dehors from 4th position. The validation consisted of a timing comparison between a three-dimensional motion capture system, and a wearable sensor. This was carried out using a Will Hopkins' Typical Error of the Estimate test.

Results: Results indicated trivial error between the two systems, with a near-perfect correlation (r = 0.99996), demonstrating the feasibility of wearable sensors for timing analysis of pirouettes. The narrow confidence limits further supported the high precision of the wearable sensor technology.

Conclusions: The results of the validation study show that wearable sensors are a valid technology for the timing analysis of pirouettes when compared to the gold standard. At this point, the data indicates that wearable sensors may be an effective tool to assist in the coaching and development of pirouettes in ballet, although further research is recommended.

Introduction

Technology has become a widely integrated training tool for many sports-based athletes and teams (Windt et al., 2020). However, across many forms of dance, technology is more often used to enhance visual performance aspects, such as transforming dancers' movements into interactive lighting projections (Mullis, 2013). Technology is less frequently utilised to assist dancers in improving their technical prowess through detailed biomechanical or physiological analysis, particularly in training situations. This differs from elite sportspeople, despite many aspects of dance performance being comparable. For example, high levels of physical demands and similar rates of injury (Moita et al., 2017) exist for both elite dancers and elite athletes. Additionally, elite dancers and athletes are often subject to comparable high psychological demands and associated issues (Quested & Duda, 2011). Similarly, at the elite or professional level, the margin for improvement is decreased relative to novice dancers or athletes.

Ballet is primarily aesthetically focused. Therefore, each dancer’s movement strategy is adapted for their own body morphology and the demands of the specific situation (Hopper et al., 2018). As aesthetics are subjective, some parameters of dance might be observed qualitatively, such as the dancer’s emotions conveyed by a movement. Even so, as for many sports-based disciplines, movement outcomes should be consistent and in-line with technical expectations for the execution of the movement. If the industry expectation is that elite dancers strive for high performance, just like elite athletes, it should be assumed that dancers have access to valid technologies that can enhance their dance capabilities just as other sportspeople do. As each coach has differing perspectives and experience, the quantitative assessment offered by technology allows all dancers to be assessed with reduced potential biases (Park et al., 2015). The gold standard technology of three-dimensional (3D) motion capture camera systems tends to be costly, time-consuming and requires a relatively high level of expertise to operate (Lee et al., 2010). Therefore, there exists a need to validate and introduce relatively easy-to-use technology into dance studios that could potentially improve training and performance protocols.

Within ballet, movements are often named by their technical description and requirements, such as the pirouette en dehors. The pirouette en dehors from 4^{th} position is a turn where the dancer leaves the preparation position (Figure 1a) and rotates away from the supporting leg in a retiré position (Figure 1b) (Hiraga et al., 2020). The leg supporting the dancer’s body weight is referred to as the supporting leg and is in a closed-chain position (Lin et al., 2013). This is the leg that the dancer turns around to complete one or more rotations. The other leg is called the working leg and is held above the floor in various open-chain positions (Lin et al., 2013). All ballet dancers are required to perform pirouettes in their daily training and in various performances, regardless of sex. The regular use of the pirouette, combined with the complexity of the movement pattern, makes the pirouette an important ballet movement and the target of this research.

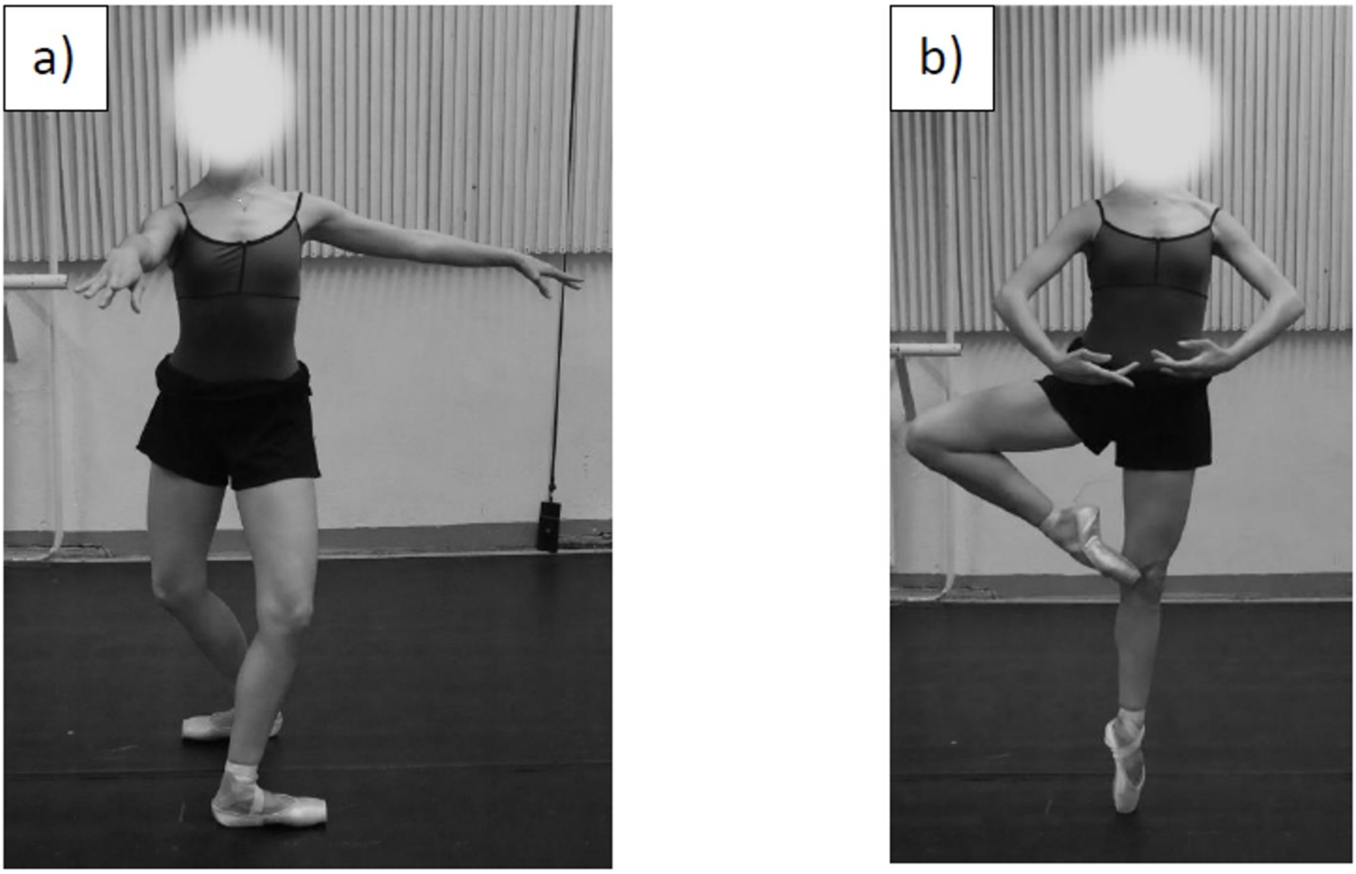

Figure 1. a) 4th position preparation for pirouette en dehors; b) retiré position.

Research has shown that wearable sensors have the potential to support judges in sports such as racewalking by way of highlighting potential illegal steps (Lee et al., 2013). Sensors with Global Positioning System, heart rate and acceleration monitoring capacities are also regularly used during training across a range of sports to track player movements and quantify training loads (Akenhead & Nassis, 2016; Seçkin et al., 2023). Furthermore, FIFA (the international governing body of football) has recently changed the governing rules to allow the use of wearable technology during competitions (Harkness-Armstrong et al., 2022). The potential benefits of wearable sensors outweighed pre-existing rules against the use of electronic devices. These changes in governing rules demonstrate that wearable sensors are often commonplace in sports training and are continuing to gain acceptance in elite competitions. Therefore, the use of wearable sensors across varied applications indicates the likelihood that technology would not be a physical danger or prolonged distraction if introduced into the ballet studio.

There is a paucity of literature pertaining to the use of wearable devices within ballet as a training and development tool. Research conducted with other elite performers shows the potential benefits of wearable technology. For example, measuring the consistency of a gymnast's movement throughout training can highlight technical problems and monitor improvements (Baudry et al., 2008). There are technical and artistic commonalities between ballet and gymnastics, indicating similar findings on the use of wearable technology may be found. Wearable sensors have also shown potential in identifying injuries and injury-causing movement patterns early in their development during football activities (Ahmadi et al., 2014). Therefore, wearable sensors may be able to assist dance coaches in the training of ballet dancers and provide an increased understanding of the kinematics of a movement that may facilitate technical improvements and limit the impact of injuries. Currently, dance coaches generally rely on their own expertise and use visual assessments as a means of giving feedback, which could occur in real-time or by using two-dimensional video recordings. The introduction of wearable sensors may provide coaches with extra resources to draw upon, therefore enhancing the training and performance of dancers.

Aim

Although many sport research findings can be applied to dance, there is little research exploring the potential benefits of wearable technology in ballet training and performance. This creates a research gap in dance-specific scientific literature. Therefore, the aim of this study was to validate and determine the levels of agreement in timing between wearable sensor technology, specifically accelerometers, and 3D motion capture system when dancers perform a pirouette en dehors from 4th position.

Methods

Nine healthy participants from the Australian Ballet School in Melbourne volunteered for this study. The Australian Ballet School holds an extensive audition process, and students accepted into the school are of elite standard. The full-time program at the Australian Ballet School consists of levels 4-8, with the level a student is placed being reliant on both age and technical ability. To participate, students were required to have no injuries that could have impacted their ability to perform pirouettes, and to be enrolled in levels 5 and 7 at the Australian Ballet School at the time of data collection. Prior to participation, the students attended an information session detailing their rights and the researchers' obligations, and an information sheet was provided for legal guardians. Additionally, the students had opportunity to ask questions about the study. Following this, informed consent from the students (and legal guardian where appropriate) was obtained in accordance with ethical guidelines. In line with the 1964 Declaration of Helsinki regarding ethical research, approval was provided by the Charles Darwin University Human Research Ethics Committee (No. H23050).

Experimental protocol:

The participants were instructed to perform a self-directed warm-up prior to testing. Dancers, like athletes, personalise their warm-up to suit their own physical characteristics, psychological needs, and upcoming movement requirements (Winwood et al., 2019) and so no standardised warm-up was imposed across participants to negate any increased injury risk. Participants wore their training uniforms that consisted of tight-fitting clothing, which has been shown to have a trivial impact on the accuracy of wearable sensors (Gleadhill et al., 2018). All participants performed the pirouettes in their ballet flats to provide consistency across both sexes.

Participants performed single, double, and triple pirouettes en dehors from a 4th position preparation. Each turn type was completed three times to the participant's preferred turning side (Andrade et al., 2020). This equated to nine pirouettes per participant. It was indicated to the participants when the technologies were ready, and they performed the trials at their own pace, with time to rest between trials as they needed. This simulated a situation where the dancers typically practice the movement without external interference. Participants performed a synchronisation heel strike before and after each pirouette trial (described in detail below).

Equipment:

An Optitrack Motive 3D infrared camera system (NaturalPoint Inc, Corvallis,

Oregon, USA, Version 2.2.0) recording at a sampling rate of 100 Hz provided the gold standard data for human movement (Ozkaya et al., 2018), and was the criterion variable for the purpose of the validation analysis (Hopkins, 2015). Acceleration data were collected by ActiGraph GT9X+ accelerometers (ActiGraph LLC, Pensacola, Florida, USA), at a sampling rate of 100 Hz. An elasticised belt was placed on the participants with a single wearable sensor and single reflective marker positioned over their L5-S1 vertebrae, the external point closest to the participant's centre of mass (Winter et al., 2016) (Figure 2). The collected sensor data were called the practical variable for the purpose of the validation analysis (Hopkins, 2015). The primary author set up, calibrated, and initialised all equipment to the relative manufacturer's instructions.

Figure 2. Image depicting sensor and reflective marker positioning at L5-S1. *Note: the sensor*

was secured inside a tight-fitting pouch and the reflective marker was placed over the external portion of the pouch.

Data Analysis:

At the commencement of each participant's data collection period, a local timestamp was simultaneously recorded in both datasets. This enabled the alignment of the data from the Optitrack and Actigraph systems for each participant. Precise synchronisation of both technologies was facilitated by the participants performing a single heel strike before and after each pirouette trial. A heel strike is a vertical movement that creates an identifiable spike in the data. It consists of the participant plantarflexing their ankles, i.e. rising onto their toes, and then lowering their heels forcefully towards the floor (dorsiflexion). This creates an impact between the heel and the ground, which can be identified and used to synchronise data across the wearable sensor and motion capture. This allowed frame-to-frame alignment of each pirouette. This method has been previously validated and reported (Lee et al., 2010).

The pirouette was the only ballet movement that was analysed. Raw linear acceleration data from the wearable sensor were collected and validated against the corresponding 3D motion capture data. Validation was completed using the timing of the data spikes created by the participants performing a heel strike. The number of frames between heel strikes for both the motion capture and acceleration data was recorded for each pirouette.

Data were processed using the ActiLife software program (ActiGraph LLC, Pensacola, Florida, USA, Version 6.13.4). The raw accelerometery signals were converted from gt3x files to CSV format and saved and exported to Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA, Version 4.90.4).

The data were then analysed with a Will Hopkins' Typical Error of the Estimate (TEE) analysis (Hopkins, 2015) in Microsoft Excel (Version 2309). A modified Cohen scale was implemented to provide thresholds for the interpretation of the data. The modified Cohen scale used is as follows: <0.1, trivial; 0.1-0.3, small; 0.3-0.6, moderate; 0.6-1.0, large; 1.0-2.0, very large; >2.0, extremely large (Hopkins, 2015). To use the modified Cohen scale on the results, the standardised raw error was used. Standardisation was automatically carried out by the Hopkins (2015) validation software. The correlation was calculated using a Pearson's correlation (r) test, with the coefficient classified according to Hopkins' correlation coefficient scale: <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; >0.9, nearly perfect; 1, perfect (Hopkins, 2002).

Results

The TEE (Figure 3) showed the standardised error between the 3D motion capture system and the sensor to be trivial with a low range between the lower and upper confidence limits (CL) (Table 1). Results were consistent across the single, double, and triple pirouettes that were performed. Furthermore, the combined results of all pirouettes were observed to be trivial (Table 1). The Pearson's correlation of r= 1.00 supports this result when rounded to two decimal places. When expanded to five decimal places, Pearson's correlation becomes r=0.99996, indicating the trivial level of error that is present.

Table 1. Results of Typical Error of the Estimate (TEE), separated by pirouette type.

Pirouette	TEE Raw units (± CL)	TEE Standardised	Pearson Correlation
Singles only	2.11 (1.72 - 2.76)	0.01 (0.00-0.01)	1.00
Doubles only	1.73 (1.37-2.27)	0.02 (0.01-0.03)	1.00
Triples only	1.65 (1.31-2.26)	0.02 (0.02-0.04)	1.00
Combined	1.86 (1.63-2.17)	0.01 (0.01-0.01)	1.00

Discussion

The aim of this research was to validate and determine the levels of agreement between a wearable sensor and a 3D motion capture system when dancers performed a pirouette en dehors from 4th position. The validation was completed to determine whether wearable sensors have the capability to record the performance of pirouettes with timing comparable to the gold standard, a 3D motion capture system. While prior research has confirmed that 3D motion capture can analyse pirouettes (Imura & Iino, 2018; Lott & Xu, 2020), little has been published using wearable sensors for pirouettes, and no known validation has been completed to measure the timing accuracy of wearable sensors during pirouettes in comparison to the 3D motion capture system.

The trivial result of the Typical Error of the Estimate and the perfect correlation (Table 1) demonstrates the validity of using wearable sensors when measuring pirouettes. The narrow band between lower and upper confidence limits demonstrates high levels of certainty in the data (Hopkins, 2015). The results showed trivial differences between the technologies for single, double, and triple pirouettes. Therefore, it was concluded that the validation of using wearable sensors to assist in the analysis of pirouette timing was successful. This is in line with existing literature demonstrating the validity of the use of wearable sensors in other sports (e.g. Evans et al., 2022; Gleadhill et al., 2016; Lee et al., 2010), which also provided the platform for the research protocol within this research. Therefore, ballet may also benefit from this research through the development of monitoring tools to aid in coaching pirouettes.

Data were separated into different sets for each pirouette trial, and the timing was measured in each dataset. This was to mitigate the potential effects of temporal drift, which can develop over time and can result in difficulties in synchronisation (Qiu et al., 2016). Most technology has drift in timing (Guggenberger et al., 2015), however when managed this is negligible. Given the proactive measures taken to curtail temporal drift in the wearable sensor data, it was anticipated that the wearable sensor and 3D motion capture camera system would both accurately measure the same timing. This was supported by the finding of trivial difference in the results of the validation (Table 1) and demonstrates the capacity of wearable sensors to achieve the levels of temporal precision present with the gold standard technology.

In the validation analysis, data from both sexes, skill levels and pirouette types were combined. This is because the analysis measured only the number of frames each pirouette was completed in, with participant characteristics and movement quality not considered a variable for the analysis. Previous research has performed timing validations for wearable sensors (Evans et al., 2021; Gleadhill et al., 2016). In this study, most pirouettes were completed in 400 to 900 frames, or 4 - 9 seconds, regardless of whether they were single, double, or triple pirouettes. While this varied due to participant preparation times and relative turning speed, the difference between the number of frames recorded by the 3D motion capture system and the wearable sensor was trivial. Furthermore, this remained the case for the single outlier (Figure 3), a participant with less training and experience than most other participants. Although that participant took almost double the amount of time to complete the turn, the difference between technologies remained trivial, with only 0.02 seconds difference. This shows that even with vastly different skill levels, the error between technologies remains statistically insignificant. The resulting assumption can be made that similar results with trivial differences between wearable sensors and 3D motion capture systems could be achieved through studies with a different population or other ballet movements.

Conclusion

While the timing of a pirouette alone is insufficient to perform a comprehensive technique analysis, the validation of wearable sensors for use in the analysis of pirouettes en dehors from 4th position will allow for the development of relevant analyses. This is the first known validation of wearable technologies for applications in ballet. While this study specifically focused on pirouettes, it provides the platform for the development of the use of wearable sensors into other technical aspects of dance analysis.

Recommendations

Future research is recommended to build upon the findings from this study. This research allowed the participants to turn at a speed comfortable for them, without a standardised timing system. To make full use of the timing capacities of the wearable sensors, it is suggested that future research should implement a system, such as music, to ensure consistent timing across all pirouettes and participants (Kim et al., 2014). Additionally, it may be beneficial for more data to be captured in a wider range of scenarios, such as with higher- and lower-skilled dancers or different turning combinations. This may enable the scope to develop normative data. The normative data can then be used to compare the pirouette in question to those of a standardised rating. As a validated technology for pirouettes in ballet, wearable sensors can now be used in future research regarding pirouettes, and subsequent studies can be designed to enhance the visual and technical analysis capabilities of the sensors.

Statements and Declarations

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Conflicts of interest

The authors declare no financial or personal relationship with any organisation or people that would influence the outcomes of this research.

Author Contributions

McDonald-Spicer, Lee and Evans contributed to the study concept and design. McDonald-Spicer and Evans collected the data. McDonald-Spicer, Lee and Evans contributed to data analysis and interpretation. All authors contributed to writing, review, and revisions.

Data availability statement

Ethical clearance for this research only allows for the results from the analysis to be publicly available. Therefore, raw data collected during this research is not available without further ethical clearance.

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