Performance Comparison of Xsens DOT and OpenPose in Estimating Posture in Running

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ABSTRACT

In the field of sports, there are many techniques for measuring running posture while the IMU-based Xsens DOT and the computer vision-based OpenPose are commonly used. These techniques have different advantages and limitations. Of these, their validity and accuracy are of particular importance. In this research project, we had 6 participants wear Xsens DOT sensors and run on a treadmill under the observation of a camera. We collected data from the sensors, processed it, and obtained their cadence and vertical oscillation during running. Subsequently, we compared these data. Based on this, we also discussed the use scenarios of these systems to help choose system when designing a running feedback system.

KEYWORDS

Xsens DOT, OpenPose, vertical oscillation, cadence, accuracy and validity, comparison

1 INTRODUCTION

Running is one of the most popular sports in the world [1], and several running feedback systems have emerged which involve various kinematic parameters such as cadence and vertical oscillation. By utilizing a running feedback system, it is possible to decrease the risk of injuries and enhance running performance[14]

Cadence refers to the frequency of steps during running or any other repetitive movement which is commonly expressed as the number of steps per minute. Cadence data can be found in the statistics provided by almost all smartwatches and fitness apps. This is not only because it is easier to calculate but also because research has shown that increasing running cadence is a means to improve performance and reduce impact forces.[9] Therefore, cadence is an important metric in the running analysis as it can provide insights into running efficiency, stride rate, and overall performance. Vertical oscillation refers to the vertical displacement or movement of the body's centre of mass during running or other forms of locomotion. It represents the up-and-down motion of the body as it moves through each stride or step. Vertical oscillation is typically measured by tracking the vertical displacement of a specific body point, such as the torso or pelvis, and is often expressed in units of distance, for example, centimetres. In the process of running, our goal is horizontal movement. Therefore, reducing vertical oscillation helps improve the running economy by minimising the energy expenditure associated with vertical motion. Vertical oscillation tends to increase during exercise fatigue, indicating a decrease in running economy as more energy is wasted in the vertical direction. When the vertical oscillation is larger, it typically indicates a slower cadence. A study examined the relationship between cadence, vertical oscillation, and lower limb loading during running. The findings indicated that lower vertical oscillation and higher cadence are associated with reduced peak vertical ground reaction forces (vGRF), with lower vertical oscillation having a more pronounced effect.[2]

It can be concluded that increasing cadence and reducing vertical oscillation are significantly correlated with improving running performance and reducing the risk of injury.

Although many smartwatches and wristbands offer measurement capabilities for these parameters, there are still many people who use professional tools such as OpenPose and Xsens DOT. With the advancement of technology, wearable sensors are being used by more people, and Xsens DOT is one such wearable sensor based on IMU (inertial measurement unit). IMU-based sensors are generally considered to have better performance. On the other hand, OpenPose, which is based on computer vision, is a relatively new technology. However, it has already found numerous applications[3][16][7][13]. Unlike Xsens DOT, it does not require users to wear sensors and only needs at least one camera to function.

The Xsens DOT is based on an IMU, and therefore, its accuracy is strongly influenced by the intensity of the movement; for example, vibration caused by poorly fixed sensors during running may interfere with the results. Due to the need to use the sensor, the location of the sensor, as well as environmental disturbances, can have an impact on it.

In the case of OpenPose, which is based on computer vision, the accuracy of the system is therefore influenced by the quality of the images. For example, insufficient lighting or low image resolution may make it difficult for the system to identify key points in a joint. Research has shown that simply changing the lighting or clothing can have an impact on the measurements obtained with OpenPose.[15] Similarly, overly complex or intense movements can affect accuracy.

Both OpenPose and Xsens DOT have been evaluated in the literature for their accuracy and reliability[11][10]. However, these articles focus on assessing the performance of one system. A few studies are comparing their accuracy, but more often, Xsens is used as a standard to verify whether OpenPose is accurate enough.[12] Some studies have shown that OpenPose has low accuracy in measuring joint angles during walking and running, making it more suitable for applications such as motion gaming or virtual reality interactions rather than kinematic analysis, where accuracy is lacking due to the inherent limitations of markerless systems[5]. However, other research suggests that while OpenPose may have low accuracy in measuring joint angles, it is more accurate in measuring lower limb movement trajectories, similar to IMU measurements. Additionally, two separate studies found that OpenPose provides accurate measurements of joint angles in patients with arthritis and accurate gait analysis in older adults. Based on previous research, it can be inferred that OpenPose performs well in measuring slower movements but has poorer performance in fast movements. It is important to note that the aforementioned studies primarily focus on the measurement of joint angles, which involves complex calculations and requires accurate measurement of multiple key points. However, in our study, we are measuring data that is of greater interest to runners, such as cadence and vertical oscillation. Calculating these metrics requires fewer key points, which may potentially improve the accuracy and effectiveness of OpenPose. Unlike accuracy, there is relatively less comparison between Xsens DOT and OpenPose in terms of their validity. The majority of studies on Xsens DOT have indicated its moderate to high level of validity. Regarding the validity of OpenPose, studies have compared it with marker-based systems and demonstrated its high effectiveness in measuring joints such as the knee. However, its validity is relatively lower when it comes to measuring the pelvis.

Therefore, we will recruit participants to run on a treadmill at different speeds. Data collected from Xsens DOT sensors and the camera will be recorded at different output rates or frame rates. We will analyze the differences between these two methods in terms of cadence and vertical oscillation. Then we analyse the accuracy and effectiveness of measurements obtained from Xsens DOT and OpenPose, aiming to provide meaningful interpretations that assist the intended audience in making actionable choices when designing running feedback system.

In this study, we will compare the performance of OpenPose and Xsens DOT. Specifically, we have the following research questions:

- Are there significant differences in cadence measurements between OpenPose and Xsens DOT?
- Are there significant differences in vertical oscillation measurements between OpenPose and Xsens DOT?
- What are the validity of measurements obtained from OpenPose and Xsens DOT?
- From the above results, what conclusions can we draw regarding the selection of an appropriate system for designing a running feedback system?

In the end, we will present the advantages and disadvantages of both systems, as well as guidance on how to make a selection.

2 RELATED WORK

Real-time running feedback is a hot topic. Existing papers focus on correcting running posture, reducing the risk of injury, improving performance, and reducing running interruptions.[14].

There are numerous pieces of literature available comparing the performance of OpenPose and Xsens DOT. One of them is to compare the performance in measuring gait parameters in older adults. In this study, the authors mentioned that OpenPose showed good accuracy in measuring lower limb range of motion (ROM) in the sagittal plane, but its accuracy was lower for pelvic and hip joint movements in the frontal plane[10]. In our study, we discussed that cadence can be calculated using changes in knee joint angles or the vertical oscillation of the hip joint. However, even if OpenPose's measurement of hip joint ROM is not accurate, we can still obtain reasonably accurate cadence by relying on its pattern of variation rather than its ROM. For measuring vertical oscillation, although we are measuring the movement of the hip joint relative to the ground, the accuracy of this measurement could still be affected.

There is another piece of literature that describes a gait analysis system based on OpenPose. Unlike our study, this system utilized two cameras and compared different placement positions. In this article, it mentions some limitations of IMU, such as susceptibility to interference from ferromagnetic materials. The article also states that OpenPose's measurements of motion trajectories are comparable to Xsens DOT. However, OpenPose tends to miss some key point data. Furthermore, from the figures in the article, it can be observed that there is a significant difference between Xsens DOT and OpenPose in the measurement of the sagittal angle of the right ankle.[6]

The authors of the aforementioned literature subsequently conducted further research on the performance of the mentioned system. The results of this study indicated that OpenPose showed relatively accurate measurements of motion trajectories. However, in some cases, there were significant errors in measuring joint angles, but the errors were smaller when the joints were simultaneously visible to both cameras. The study suggested that their system could be used for applications like video games but may not be sufficient for comprehensive kinematic analysis.[5]

3 METHODS

3.1 Participants

The participants were all students from the University of Twente. A total of 6 participants took part in the study. Participants were informed about the potential risks of joint or body pain and fatigue associated with the experiment. They all signed informed consent forms. The study was approved by the Ethics Committee of the University of Twente. Inclusion criteria included having an average weekly running distance of over 2 kilometers for more than 6 months, being able to run at a speed of 10 km/h for 2 minutes, and having experience with running on a treadmill. Exclusion criteria included any injuries or surgeries on the knee joint or ankle within the past six months.

3.2 Task

Participants were instructed by the researchers to gradually increase the speed on the treadmill to 7 km/h. Once the participants' running posture was stable, the researchers simultaneously recorded data using Xsens DOT and a smartphone for video recording. After recording data for 1 minute, participants were instructed to rest. Then, participants gradually increased the running speed on the treadmill to 10 km/h, and the recording process was repeated as before.

3.3 Senor

Xsens DOT is a wearable sensor based on inertial measurement unit (IMU) technology. The Xsens DOT sensor has a sampling rate of 600Hz and an acceleration range of 16g[4]. In this study, we recorded data using an output rate of 120Hz. The sensor was placed directly in front of the participant's pelvis and securely fastened using the official Xsens elastic strap(see Figure 1).

Figure 1: Sensor Placement

Figure 2: Camera Placement

3.4 Computer

The computer used to run OpenPose was equipped with an Intel I7-9750H @2.60 GHz CPU and an Nvidia GTX 1660Ti GPU.

3.5 Camera

We used the camera of a Samsung S22 smartphone for recording, with a resolution of 1920*1080 and a frame rate of 120Hz. During the recording process, the smartphone was mounted on a tripod at a height of 128 cm and positioned at a distance of 195 cm from the treadmill(see Figure 2, the camera is placed in the red circle). The forearm length of each participant was measured for the purpose of calculating the vertical oscillation.

3.6 Video processing

Due to the presence of windows in the background of the original videos, there were some reflections captured. To avoid interference with the recognition of participants by OpenPose, we performed video editing to cover up the reflections on the glass. Additionally, to process the data within a limited time frame(which could be important for a real-time feedback system), as OpenPose operates at a speed of 3 frames per second (FPS) on the researcher's computer, we downscaled the original 120 FPS videos to 30 FPS.

3.7 Gait variables

The gait variables in this study are cadence and vertical oscillation. We use different methods to calculate them in Xsens DOT and OpenPose as they have different principles and output types. The IMU-based Xsens DOT provides mechanical parameters including acceleration and Euler angle. To obtain the cadence data, we find the high peaks in the acceleration data on the Z axis which is vertical to the ground. These peaks occur at the moment when the participant(runner) contacts the ground. An interval between two peaks is one step time in the scale of the data frame. As we know the output frame, we can calculate each frame time. Then each step costs frame multiply frame time second. The inverse of step time is the cadence (per second) which can be multiplied by 60 to get the cadence(per minute).

For the calculation of vertical oscillation, we need to integrate the accelerations to get the velocity, where $t_0$means the moment of a low peak in acceleration data and t_1 means the moment of the next peak:

$$v = v_0 + \int_{t0}^{t1} a\mathrm{d}t$$

After that, we integrate the velocity to get the displacement(vertical oscillation):

$$d = \int v\mathrm{d}t$$

The computer vision-based OpenPose provides spatial data: the key points of the body in coordinates. So the method to calculate the vertical oscillation is to find the lowest and highest point in one step. Then by doing the deduction, we can get the vertical oscillation in coordinates. Because we already have the length of the forearm of each participant, we can then transfer the coordinates to the physical unit (cm).

For the cadence, we calculated the knee angle by the law of cosines. Following is the formula to calculate the knee angle where a is the vector of the calf and b is the vector of the thigh.

$$\theta = \arccos\left(\frac{\mathbf{a} \cdot \mathbf{b}}{\|\mathbf{a}\| \cdot \|\mathbf{b}\|}\right)$$

To get the length of a and b we can use the distance formula:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

where (x_1,y_1) and (x_2,y_2) are the starting point and ending point coordinates of the vector. By observing the periodic changes in the knee joint angle, we can obtain the cadence or cadence of a single leg. Then the cadence is the cadence of a single leg multiplied by 2.

3.8 Statistical analysis

All the cadence and vertical oscillation data are already filtered by the 1.5 IQR rule to exclude outliers and then be compared.

First, we will use descriptive statistics to compare the means and variances of the two systems at different running speeds. The variance represents the degree of dispersion in the data, which to some extent reflects the stability and validity of the measurements. Due to the fact that the cadence and vertical oscillation data obtained from OpenPose and Xsens DOT have the same units, it is sufficient to analyze them using standard deviation alone, without

Table 1: Cadence in 7 km/h

Participant	OpenPose		Xsens DOT(60Hz)		Xsens DOT(120Hz)	
	Mean	SD	Mean	SD	Mean	SD
1	153	4.8	156	13.0	155	12.3
2	143	4.4	160	36.9	139	20.7
3	145	6.5	143	8.9	139	50.3
4	145	3.0	145	3.3	146	8.3
5	158	5.2	154	4.1	158	8.5
6	164	8.8	165	11.2	170	29.0

Table 2: Cadence in 10 km/h

Participant	OpenPose		Xsens DOT(60Hz)		Xsens DOT(120Hz)	
	Mean	SD	Mean	SD	Mean	SD
1	156	4.7	154	5.4	156	3.7
2	148	2.7	177	3.5	153	20.0
3	164	0.0	149	11.2	263	69.0
4	161	10.9	153	4.5	153	5.7
5	173	13.3	172	9.4	174	13.3
6	165	8.0	169	24.1	170	29.0

Table 3: Vertical oscillation in 7 km/h

Participant	OpenPose		Xsens DOT(60Hz)		Xsens DOT(120Hz)	
	Mean	SD	Mean	SD	Mean	SD
1	4.7	1.67	9.8	2.68	9.2	2.50
2	8.5	2.08	10.2	2.39	8.7	2.42
3	12.2	1.82	9.5	2.61	8.3	1.98
4	11.3	1.08	9.7	2.26	11.8	1.59
5	4.8	1.4	9.1	2.68	11.3	2.04
6	5.7	1.8	10.1	2.13	11.6	1.89

Table 4: Vertical oscillation in 10 km/h

Participant	OpenPose		Xsens DOT(60Hz)		Xsens DOT(120Hz)	
	Mean	SD	Mean	SD	Mean	SD
1	6.0	1.45	11.1	1.82	10	2.27
2	10.8	2.29	9.1	2.25	8.7	2.24
3	9.7	3.88	8.6	2.29	10	2.50
4	10.7	1.04	10.0	2.20	12.3	1.31
5	5.48	1.72	7.9	2.06	11.5	1.73
6	7.8	1.4	8.2	2.27	7	1.59

the need for a coefficient of variation. Our data from the six participants' running sessions are assumed to be independent. Due to our small sample size, it is necessary to conduct a normality test so we will test the normality by the Shapiro-Wilk test which is an appropriate method for small sample size($3 < N < 50$). Then we will use the Pearson correlation coefficient to assess the correlation between the means of the two systems. Next, we will draw Bland-Altman plots to further analyze the agreement between the two systems[8]. It is important to note that correlation does not imply agreement, and we will further explain the implications of these comparisons in the discussion. We will also present the measurements from both systems in graphical form to provide users with a visual understanding.

4 RESULTS

We recorded running videos at 120 frames per second (FPS), but due to processing speed limitations, we ultimately decided to use OpenPose with a video frame rate of 30 FPS. Unless otherwise specified, the data from OpenPose and Xsens DOT are respectively based on a frame rate of 30 FPS and a data output rate of 60 Hz.

4.1 Descriptive Statistics

See Table 1 2 3 4 We conducted descriptive statistics on the measurement results and found that OpenPose and Xsens had similar measurements for cadence, but Xsens DOT had a significantly higher standard deviation. We also observed that increasing the data output rate did not necessarily increase or decrease the standard deviation. For vertical oscillation measurements, there were significant differences between the results of OpenPose and Xsens DOT. Additionally, at a speed of 7 km/h, OpenPose had a lower standard deviation than Xsens DOT, while at 10 km/h, OpenPose had a higher standard deviation than Xsens DOT.

Table 5: Cadence 7 km/h

Correlations

		OP	Xsens
OP	Pearson Correlation	1	.609
	Sig. (2-tailed)		.199
	N	6	6
Xsens	Pearson Correlation	.609	1
	Sig. (2-tailed)	.199	
	N	6	6

Table 6: Cadence 10 km/h

Correlations

		OP	Xsens
OP	Pearson Correlation	1	-.093
	Sig. (2-tailed)		.861
	N	6	6
Xsens	Pearson Correlation	-.093	1
	Sig. (2-tailed)	.861	
	N	6	6

4.2 Pearson Correlation Coefficient

See Table 5 6 7 8 Before conducting the Pearson correlation test, we performed the Shapiro-Wilk test for normality on the data, and the distribution of the data did not show significant deviation from normality. Since we analyzed data from different sets of 6 participants each time, we satisfied the assumption of independence. According to the results of the Pearson correlation test, for the cadence data at 7 km/h, $r=0.609$, $p=0.199>0.05$. This indicates a positive correlation between OpenPose and Xsens DOT under this condition, but the p-value is greater than 0.05, indicating that this conclusion is not statistically significant. For the other three sets of data, both the correlation and significance were not evident.

Table 7: Vertical Oscillation 7 km/h

Correlations

		OP	Xsens
OP	Pearson Correlation	1	.016
	Sig. (2-tailed)		.976
	N	6	6
Xsens	Pearson Correlation	.016	1
	Sig. (2-tailed)	.976	
	N	6	6

Table 8: Vertical Oscillation 10 km/h

Correlations

		OP	Xsens
OP	Pearson Correlation	1	.045
	Sig. (2-tailed)		.933
	N	6	6
Xsens	Pearson Correlation	.045	1
	Sig. (2-tailed)	.933	
	N	6	6

4.3 Bland-Altman Grpah

See Figure 3 We plotted Bland-Altman graphs for the cadence and vertical oscillation data at 7 km/h and 10 km/h using both OpenPose and Xsens DOT. Since Bland-Altman analysis does not require independence, we also compared the cadence data at both speeds together.

From the graphs, we can observe that the data points for cadence and vertical oscillation are mostly within two standard deviations. However, they are not consistently distributed around the zero line, indicating that there is some level of variability between the two systems. Therefore, we can conclude that there is a certain degree of agreement between the two systems.

See Figure 4 5 From these two graphs, it can be observed that as the speed increases from 7 km/h to 10 km/h, the data points for vertical oscillation become more dispersed. Additionally, there are noticeably more data points that fall outside the range of two standard deviations, indicating a decrease in the agreement between the two systems. This could be attributed to the higher movement speed and increased motion amplitude, which pose challenges in measurement accuracy.

It should be noted that the data from OpenPose at 10 km/h did not pass the normality test. However, according to George and Mallory (2010), since the kurtosis and skewness values are relatively small, we still accepted this set of data.

See Figure 6

From this graph of the cadence data, it can be observed that the data points from OpenPose and Xsens DOT are mostly within two times the standard deviation. However, as the cadence increases, there is a noticeable bias. This indicates that there is some level of agreement between the two systems, but there may be a systematic error present. If the cadence continues to increase, the consistency between the two systems may decrease.

4.4 Graph Comparison

See Figure 7 From the comparison graph of vertical oscillation, it can be observed that the consistency between the two systems varies among individuals. For Participant 1, the variation trend of the two systems is more similar

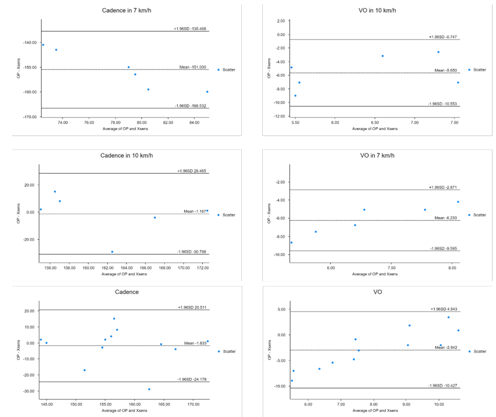

Figure 3: Overall

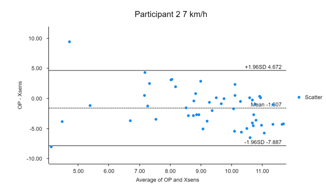

Figure 4: Vertical Oscillation

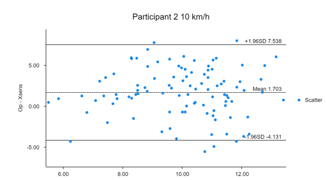

Figure 5: Vertical Oscillation

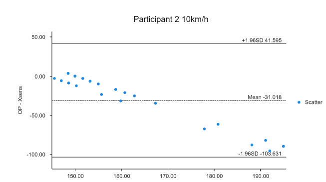

Figure 6: Cadence

See Figure 8

From the graph, it can be seen that OpenPose has a smoother variation in cadence, but with more small fluctuations.

5 DISCUSSION

In this section, we will discuss the results above.

- Descriptive Statistics

  The cadence measurement data between the two systems are similar, despite their different standard deviations while overall they are relatively low so their is no evidence shows

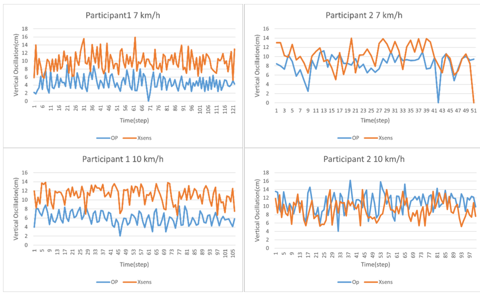

Figure 7: Vertical Oscillation

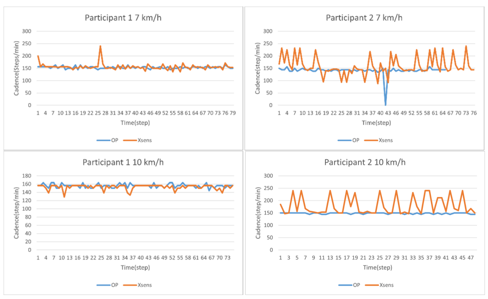

Figure 8: Compare Cadence

their validity are low. The difference in standard deviations, relative to the means, is not substantial, suggesting that the two systems perform comparably in measuring cadence. However, for vertical oscillation, there is a notable difference in the means between the two systems. Therefore, further analysis is required in the subsequent sections to investigate this difference in more detail.

- Pearson Correlation Coefficient
  By calculating the Pearson correlation coefficient, we did not find any significant linear correlation between the data from the two systems. However, it is important to note that this analysis is based on the means of the measurements. When it comes to individual measurements, the Pearson correlation coefficient may not provide conclusive results.
- Bland-Altman Grpah
  From the graphs, it can be observed that both systems exhibit a certain level of consistency in measuring cadence and vertical oscillation at both speeds. However, for vertical oscillation, there is greater variability in the distribution of data points at 10 km/h, indicating that the consistency of the two systems may vary at different speeds. Therefore, users of these two systems should consider selecting the appropriate system based on their anticipated running speed.
- Graph Comparison
  Because both systems exhibit similar trends in capturing the variations of cadence and vertical oscillation over time, there is not a significant difference between the two systems in describing the trends of running. However, when considering different participants and speeds, it is important to exercise caution with Xsens DOT as it tends to have greater fluctuations.
- Suggestions on System Selection
  OpenPose requires a tripod to stabilize the camera and ensure a stable shooting angle and quality of pose tracking. This makes it more suitable for recording treadmill running. Also, OpenPose has certain requirements for lighting conditions, as it needs sufficient light to obtain clear images, and it's important to avoid obstructions. But it only requires a single camera and does not require the purchase of additional sensors. Additionally, OpenPose has a slower data processing speed, such as with the Nvidia GTX 1660Ti graphics card, processing speed is approximately 3 frames per second, which may not meet the requirements of real-time feedback systems.
  On the other hand, Xsens DOT requires the use of sensors and elastic bands for fixation, which may cause discomfort to the runner and potentially affect their performance. However, Xsens DOT doesn't have specific requirements for lighting or obstructions, making it suitable for use in various indoor and outdoor environments. It also has a faster real-time data processing speed.
  In summary, OpenPose has a lower cost and does not require wearing sensors, so it does not interfere with the performance of the runner. Also, it is more suitable for recording running on a treadmill, and it requires proper lighting and avoidance of obstructions, and its data processing speed is slower. Xsens DOT, on the other hand, can be used in various environments without specific lighting requirements, but consideration should be given to the potential discomfort caused by wearing sensors. The choice of the system depends on the specific usage scenario and requirements.
- Limitation This study may have a relatively small sample size, and the samples may come from students in the university. This may limit the generalizability and applicability of the findings to different populations. This study has been conducted in specific testing environments: indoor and specific treadmill settings. This may limit the generalizability of the results and fail to account for the influence of outdoor environments and other factors on system performance. This study mentioned the technical requirements for the installation and data processing of OpenPose and Xsens DOT. However, these requirements may exceed the technical abilities of the average user, limiting the practical usability and adoption of the systems.
- Future work In future work, we will conduct outdoor testing to evaluate the performance of both systems under different lighting conditions. Additionally, we will expand our participant pool to include individuals of various age groups and running habits, not limited to just college students. To validate the accuracy and effectiveness of the two systems, this study only compared them to each other. In the future, we will compare these systems to established gold standards for further validation.

6 CONCLUSIONS

In this study, we compared the performance of OpenPose and Xsens DOT at two different speeds. We find that the cadence and vertical oscillation measured by these system has a certain degree of agreement. However, there are also differences between theses systems especially in a higher running speed(10 km/h). In the end, we gave the potential users suggestions on how to select an appropriate system for designing a running feedback system.

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