XSENS MVN REPORTS

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Xsens MVN Gait Report: The use of inertial motion capture for Cloud based reporting of gait parameters

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Contents

Xsens MVN Gait report: The use of inertial motion capture for Cloud based reporting of gait parameters

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Abstract

The newly released Xsens MVN cloud-based gait report is a new tool to reduce the costs associated with (clinical) gait analysis. This cloud-based system allows users to collect lab quality motion capture data in any environment and have access to reports in a secure manner with faster and earlier workflows. This paper describes the various stages of the gait cycle and its associated parameters. It presents Xsens performance against reference optical data. Overall, the data showed encouraging results across a wide range of (clinically) relevant parameters. The report further enables rich quantitative analysis in the form of joint angles, segment kinematics and centre of mass tracking, which allow many quantities of interest to be investigated. The Xsens MVN setup is completely wearable enabling the analysis of patients in their natural environment, thereby facilitating a wider adoption to the community, as well as a cost-effective solution to perform gait analysis.

1 Introduction

Three-dimensional gait analysis is a standard tool within the clinical biomechanics community. Clinical biomechanics focuses on medical and clinical applications to support clinicians to explain the causes of a variety of musculoskeletal disorders. Further, it allows methods to support diagnosis, prognosis and evaluation of treatment methods and technologies. This in turn, provides invaluable knowledge to clinicians to improve the clinical management of patients. Gait is the most common form of locomotion for humans and requires a smooth and efficient progression of the body's centre of mass (COM). To achieve this, each of the lower limb joints must undertake specific movements at specific times, in order to propel the body forward successfully. The relationship between each of these movements and timings is critical, any deviation in the coordination of these patterns increases the energy cost of walking, as well as create inefficient methods of power absorption and generation[1].

Gait analysis has traditionally been performed using three dimensional optical motion capture systems along with the implementation of reflective marker setups, to compute 3D segments and joint kinematics[2]. Optical methods can include both direct kinematics (DK) and inverse kinematics (IK). DK assumes experimental markers to be rigidly attached to bones and segments, the joint kinematics are then calculated from the Cardan angles between adjacent segments defined by the markers' 3D position[3,4]. With the emergence of musculoskeletal modelling software solutions such as OpenSim[5] and AnyBody[6], inverse kinematics (IK) has also become widely adopted by the biomechanics community for musculoskeletal research[7]. In contrast to DK, IK employs an anatomical model with markers rigidly attached to the model. The joint kinematics are then computed by adjusting the models joint angles such that the error between the modelled and experimental markers is minimized[8].

However, a limitation of 3D optical motion capture is the cost and availability of well-equipped gait laboratories, restricted measurement space and line of sight problems with the reflective markers[9], as well as having low ecological validity. Inertial motion capture addresses these shortcomings and allows the measurement of motion outside of sparse motion capture laboratories. Inertial measurement units (IMU) consist of accelerometers, gyroscopes and magnetometers, from which the position and orientation of a body segment can be estimated via the process of sensor fusion[10]. Based on this position and orientation data, joint kinematics can be determined in an ambulatory setting. Importantly, IMU's are relatively inexpensive and portable, making them accessible to a wide variety of clinical settings. Moreover, recent methods have allowed further analysis such as muscle-tendon force, joint moments and joint contact force calculations using exclusively inertial sensor data[11–13].

Recently, Xsens Technologies has dedicated significant efforts to provide the clinical community with tools that reduce the costs associated with clinical gait analysis, as well as increase its use in clinical settings. To this end, a clinical gait report has been created in order to provide the spatial and temporal parameters associated with the human gait cycle, as well as have the ability to be both created and stored in a secure cloud-based ecosystem. This has several advantages; file uploads allow the data to be processed without relying on front-end hardware. In addition to this, the cloud-based system, allows users with assigned permissions to access the reports from any location in a secure manner, improving communication amongst interdisciplinary teams.

Xsens cloud hosts the new MVN reporting functionality. MVN reporting is a tool that allows to create reports generated with Xsens recording files. These reports are used as a tool to help in the analysis and/or interpretation of multiple kinematic parameters in different tasks. These files are uploaded to a secure cloud environment called MotionCloud. The following figure demonstrates the way files are uploaded and visualized for users in a secure manner and how this works in three simple steps from logging in to uploading and report result (Figure 1).

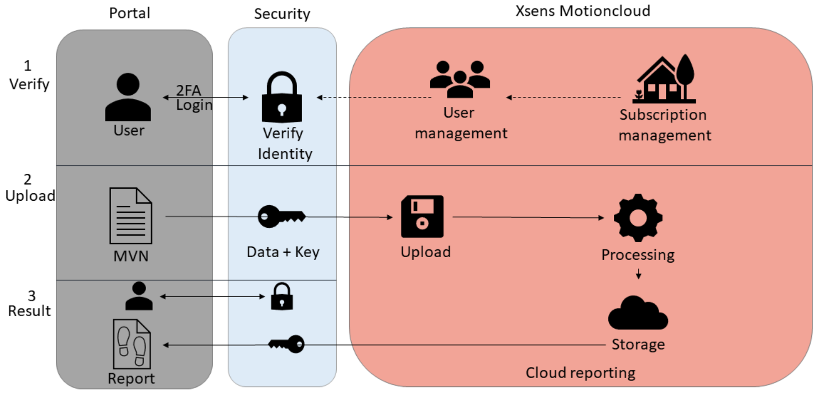


Figure 1: Xsens cloud architecture

Within the cloud reporting environment, Xsens is focusing on Health, Sports and Ergonomics reports.

This paper describes the various stages of the gait cycle and its associated spatial and temporal parameters included in the report. It provides a brief description of the motion capture system and cloud report. Finally, a comparison against an optical reference system is shown to demonstrate its validity and performance.

2 The gait report

The gait cycle

Human gait or walking can be described as a cyclic pattern of movements which advances an individual's position[14]. The gait cycle is divided into what we refer to as the stance phase and the swing phase. The stance phase, which comprises approximately 60% of the gait cycle[1], begins with the heel strike of one foot with the ground and ends with the toe off of the same foot. It is during this phase that the foot is bearing the weight of the body. The remaining 40% of the gait cycle is the swing phase, in which the foot is non weight bearing as it moves from one step to another. It begins at toe off of one foot and ends at heel strike of the same foot.

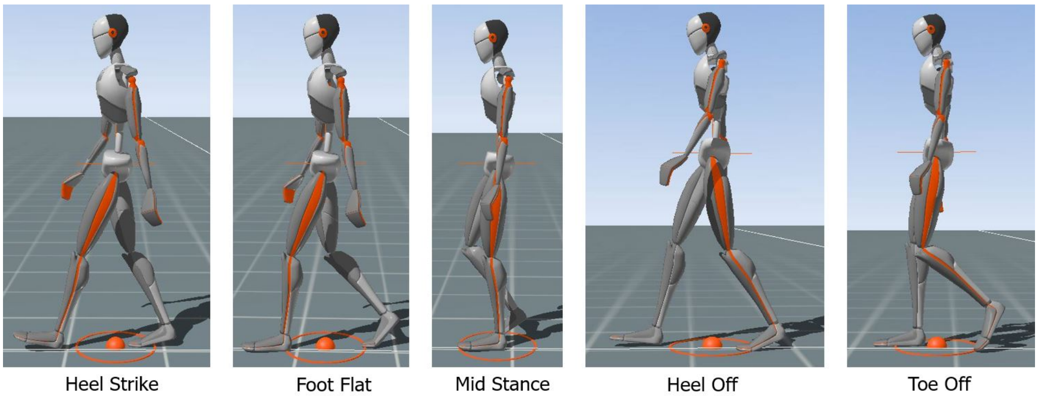


Figure 2: Specific events of stance phase for the left leg, with the direction of progression to the left.

The stance phase can be further be subdivided into specific events which are referred to as (i) heel strike, (ii) foot flat, (iii) mid-stance, (iv) heel off and (v) toe off (Figure 2). While the swing phase can be further subdivided into specific events which we refer to as (i) early swing, (ii) mid swing and (iii) late swing (Figure 3). You will often find that the events of a gait cycle are also described in percentage, rather than just time duration. This is because the exact time duration is dependent on the individuals walking velocity, which can be slow, self-selected, or fast.

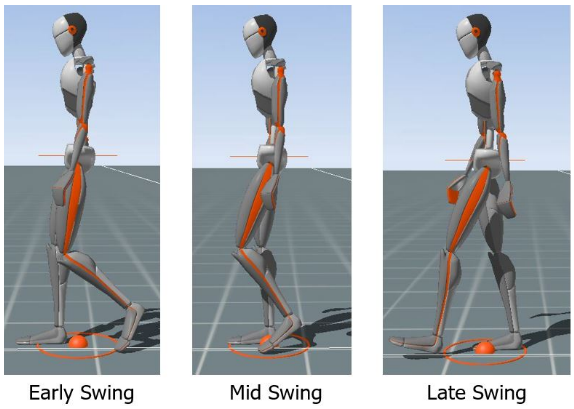


Figure 3: Specific events of swing phase for the left leg, with the direction of progression to the left

An analysis of the gait cycle can occur in several ways. As we have described earlier, we can analyse gait with respect to the foot contact times, in which the foot is either in contact with the ground or not. We can then use particular spatial and temporal parameters which allow us to draw a simple functional assessment of gait. Further, we can study it in more detail by studying the action and motion of each of the lower limb segments and joints, which enables us to interpret the movement patterns in relation to their functional contribution to walking[1].

Spatial parameters

Objective measures of gait allow us to characterize functional gait performance[15]. Computing the Spatio-temporal parameters of gait requires the identification of specific events. These events are the heel strike, or the first initial contact with the ground and the toe off, or the final contact with the ground. From these events we can deduce the following spatial parameters (Figure 4).

Step length: The distance along the line of progression between the heel strike position of the first foot, and the heel strike position of the opposite foot in the successive step. The step length is associated with the swinging leg (i.e. if the right leg is the swinging leg, the distance between the left and right heel strikes, is the right step length).

Stride length: The distance between the heel strike position of the first foot, and the heel strike position of the same foot in its successive step. This further defines the line of progression and is also associated with the start and end of each gait cycle.

Step width: The medial-lateral distance between the heel strike position of the first foot, and the heel strike position of the opposite foot in the successive step. The step width is perpendicular to the line of progression and is associated with the swinging leg (i.e. if the right leg is the swinging leg, the medial-lateral distance between the left and right heel strikes, is the right step width).

Foot progression angle: The foot progression angle (FPA) is the angle of the foot orientation away from the line of progression

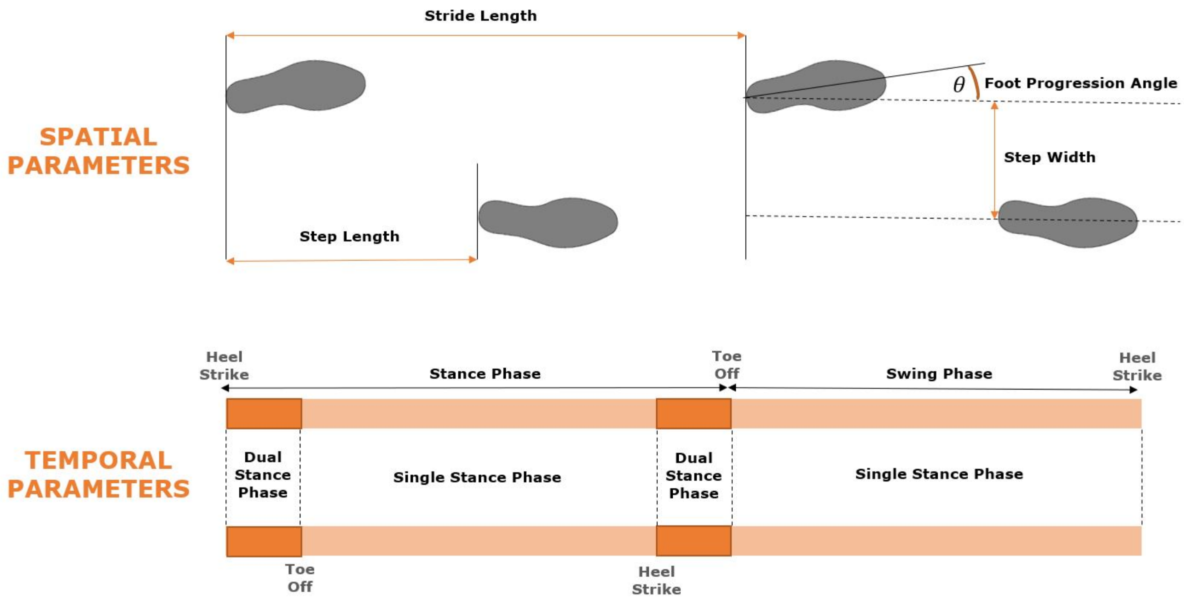


Figure 4: Spatial and Temporal parameters of gait

Temporal parameters

In addition to spatial analysis, the heel strike and toe off events of gait allow us to compute several important temporal parameters from the foot contact times. With these times we can deduce the following temporal parameters (Figure 3). As mentioned earlier, temporal parameters are also described in percentage of the gait cycle, rather than just time duration. This is because the exact time duration is dependent on the individuals walking velocity

Gait cycle or stride time: The period of time between two consecutive heel strikes from the same leg.
Step time: The period of time between two consecutive heel strikes of the opposite foot. The step time is associated with the swinging leg (i.e. if the right leg is the swinging leg, the time between the left and right heel strikes, is the right step time).
Stance phase: The period of time elapsed from heel strike through to toe off of the same foot.
Swing phase: The period of time elapsed from toe off through to heel strike of the same foot.
Single support phase: The period of time in which the body is supported by only one leg.
Double support phase: The period of time in which the body is supported by both legs.
Loading response: For a given leg, the period of time between its heel strike and the toe off of the opposite foot.
Midstance: For a given leg, the period of time between the toe off of the opposite foot (which becomes the swinging foot), and the moment the bodies centre of mass is over the support foot.
Terminal stance: For a given leg, the period of time between the moment the bodies centre of mass is over the support foot, and the heel strike of the opposite foot (which was the swinging foot).
Pre-swing: For a given leg, the period of time between the heel strike of the opposite foot (which was the swinging foot) and the toe off of the support foot.

Next to the spatial and temporal parameters we also calculate general parameters including the walking speed (meters per second) and the cadence (steps per minute). As the walking speed increases, the double support phase decreases until the stance phase and swing phase are nearly equal with very little double support time, it is at this point that the transition from walking to running occurs[1,14].

Joint motion patterns during gait

The spatial and temporal parameters allow us to draw a simple functional assessment of gait. However, we can study it in further detail by studying the action and motion of each of the lower limb segments and joints. The events of a gait cycle occur remarkably in similar sequences and are independent of time, this critical coordination allows an energy efficient progression of the person walking.

In this section, example data from a healthy participant is provided to demonstrate joint motion patterns for the hip, knee, ankle and pelvis. The hip motion can be categorised into stages of hip extension in which the trunk is stabilised during stance phase, as well as hip flexion in which the leg is moved forward during swing phase. The knee is a basic determinant of limb stability during stance, and its ability to flex is important in order to undertake the swing phase during progression[14]. While the range of motion of the ankle is not large, it is fundamental to achieving propulsion during gait. All of these motions timed appropriately allow us to achieve smooth and efficient progression of the bodies centre of mass.

The joint motion patterns analysed during gait, include the movement of the following joints along the sagittal, frontal and transverse plane.

- Hip
- Knee
- Ankle
- Pelvis orientation

The intention of the following section is not to provide an exhaustive description of each of the parameters and how they may relate to particular gait pathologies, but rather as a general description of their functional contributions during gait.

Hip motion patterns

The following figure shows how the kinematics of the hip joint is represented (*Figure 5*). The sagittal plane represents the hip flexion (+) and hip extension (-), the frontal plane represents hip abduction (+) and hip adduction (-), and the transversal plane represents internal rotation (+) and external rotation (-). The gait cycle is further broken down into stance and swing phase.

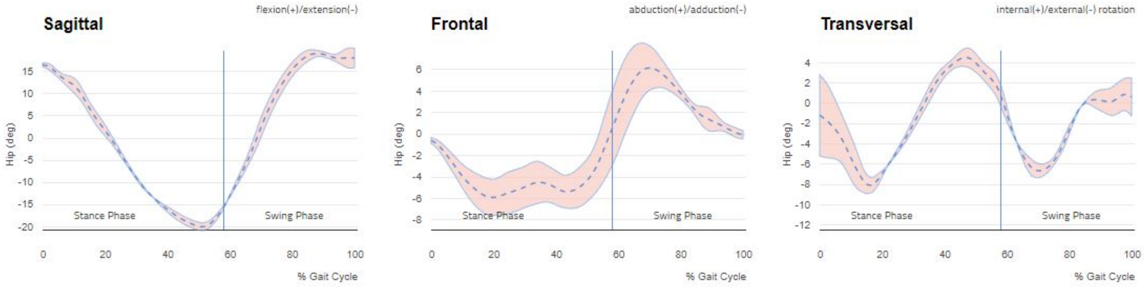


Figure 5: Hip motion pattern

If we observe, the hip enters into hip extension during stance as the trunk is stabilised while progressing the body forward. As swing phase is entered, the hip will undergo very fast and rapid flexion in order to swing the leg forward to take a step, reaching a maximum just before heel strike. During stance phase, the hip is in a position of adduction as the body is loaded on the support limb, while a subsequent drop of the pelvis occurs on the contralateral side. Once the body has moved over the stance limb, it enters into abduction as the pelvis flattens out and the leg moves into a swing phase. With respect to the transversal plane, as heel strike occurs and the limb enters stance phase, the hip will be in an externally rotated position, however once mid stance is entered and the body moves over the stance foot, the hip will rotate internally as the pelvis rotates forward on the swinging side. During swing phase the hip moves into external rotation again, as the swing leg is swung forward. There can be a considerable amount of variability in the transverse plane, as it is dependent on pelvis position, as well as femoral rotation[1].

Knee motion patterns

The following figure shows how the kinematics of the knee joint is represented (*Figure 6*). The sagittal plane represents the knee flexion (+) and knee extension (-), the frontal plane represents knee abduction (+) and knee adduction (-), and the transversal plane represents internal rotation (+) and external rotation (-).

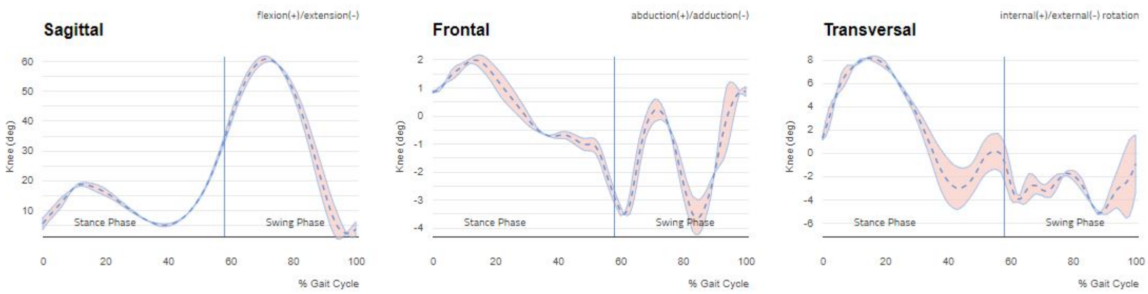


Figure 6: Knee motion pattern

If we observe, the knee enters into a small amount of flexion of approximately 20 degrees, as the body moves over the support foot acting as shock absorber as it enters its maximum weight bearing load. Following this first small peak, it enters into almost full extension, before beginning a second period of flexion during heel off. This second period of flexion occurs very rapidly in preparation for the swing phase, allowing the toe to clear the ground and swing the leg forward. During late swing, the undergoes rapid extension to prepare for heel strike of the next step. Movement along the frontal plane is often more difficult to describe and can vary between individuals, based on their degree of genu varum (bow-legged) or genu valgum (knock-knee). The motion within the transverse plane refers to tibial rotation along the femur, and the tibia will typically rotate externally during swing phase into the beginning of stance, in order for the tibia and foot to be in correct alignment prior to heel strike[16]. It is further thought during stance, that the anterior cruciate ligament (ACL) is passively loaded due to internal tibial rotation and then released during swing phase; this combined with medial and lateral condyle length differences, results in external rotation of the tibia[16].

Ankle motion patterns

The following figure shows how the kinematics of the ankle joint is represented (*Figure 7*). It is important to note that movement at the ankle joint is much more complex due to the number of segments. The movement of the foot as a whole about the tibia, referred to as ankle joint motion, is the most commonly reported movement pattern of the foot and ankle complex[1]. For Xsens MVN, the foot is split up into two joints, the calcaneus to tibia movement (ankle), and the metatarsal to calcaneus movement (ball-foot). For the ankle, the sagittal plane represents dorsi flexion (+) and plantar flexion (-). The frontal plane represents the eversion (+) and inversion (-), and the transversal plane represents supination (+) and pronation (-).

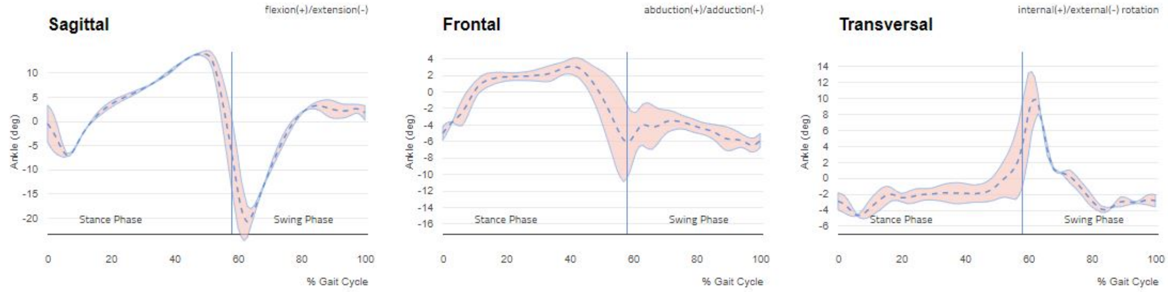


Figure 7: Ankle motion pattern

If we observe, at initial heel strike, the ankle is in a neutral position with respect to the sagittal plane, before undergoing a brief period of plantar flexion prior to foot flat. Following this the ankle undergoes plantar flexion throughout stance as the body moves through mid-stance. Prior to heel lift, a rapid plantar flexion occurs giving propulsion to the body, followed by a rapid dorsi-flexion during swing phase to allow toe clearance from the ground. At heel strike the foot is in an inverted position and will evert during stance phase while the foot is being loaded, prior to 50% of the gait cycle, rapid inversion will take place[1]. The transverse plane movement of the foot may be used as a descriptor of pronation-supination[17], this pattern shows a slightly pronated position during foot contact, before moving into a supinated position during late stance phase and into the swing phase.

Pelvis motion patterns

The following figure shows how the kinematics of the pelvis orientation is represented (*Figure 8*). The sagittal plane represents the forward pelvic tilt (+) and backward pelvic tilt (-), the frontal plane represents upward pelvic obliquity (+) and downward pelvic obliquity

(-), and the transversal plane represents internal pelvic rotation (+) and external pelvic rotation (-).

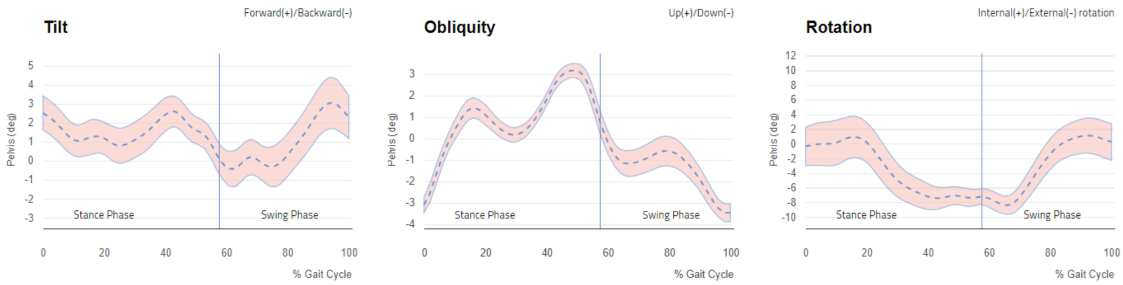


Figure 8: Pelvis motion pattern

The pelvis will typically tilt forward during heel strike of the opposite foot, and during early stance phase the contralateral side of the pelvis will drop downward along the coronal plane. The pelvis obliquity serves to absorb shock and to allow limb length adjustments[1]. The pelvic rotation will fluctuate between left and right rotation, which allows an increase or decrease in step length, as well as preventing the centre of mass from moving up and down too much.

Foot progression angle and centre of mass tracking

In addition to the joint motion patterns presented, additional insights can be gained from analysis of the following parameters, which have been added to the Xsens MVN gait report

Foot progression angle (FPA): As mentioned in the spatial parameters, the foot progression angle is the angle of the foot orientation away from the line of progression. It plays an important role in how the medial compartment of the knee joint is loaded, as it has a large impact on the knee adduction moment[18].

Centre of Mass tracking: The centre of mass (COM) is presented with respect to its position, velocity and acceleration along each of the anatomical planes. The vertical displacement of the COM has a direct impact on the metabolic cost of human walking, previous authors have found that increasing or decreasing the vertical COM displacement beyond a subject's preferred range results in an increased metabolic energy cost, due to greater mechanical work performed by the hip, knee and ankle joints[19]. Furthermore, with the COM oscillating in the vertical plane, the vertical COM velocity increases as the COM falls and is reversed prior to foot contact during the single support phase. This braking of the COM fall during the transition to double support is an indicator of balance control[20].

Upper and lower leg acceleration

The acceleration of the upper leg can show important information in how the hip flexion velocity is controlled. Prior to swing phase, the hip flexors will accelerate the femur creating hip flexion velocity in order to swing the stepping limb forward. In addition to this, the acceleration of the lower leg can show important information in how the knee flexion velocity is controlled. Knee flexion occurs very rapidly in preparation for the swing phase, allowing the toe to clear the ground and swing the leg forward. During late swing, the knee also undergoes rapid extension to prepare for heel strike of the next step.

Motion Tracking and Cloud Report

Motion capture is measured using Xsens MVN, which offers two different hardware setup options including a wireless system that samples at 60Hz, as well as a wired system that samples at 240 Hz. A total of 17 IMU's are mounted on the head, sternum, pelvis, upper legs, lower legs, feet, shoulders, upper arms, forearms and hands for full body motion capture. MVN Awinda also allows only lower body motion capture using just 7 sensors mounted on the pelvis, upper legs, lower legs and feet, which can sample up to 100Hz. The data is processed with the matching Xsens MVN software. Prior to performing trials, each participant's segment dimensions must be input into the Xsens MVN software. Using a measuring tape the dimensions are measured with the subject standing in an upright posture. These measurements consist of the distances of the ankle, knee, hip and top of head from the ground. In addition to this the inter-ASIS distance, inter-acromion and inter-dactylion distance is measured representing the pelvis, shoulder and upper arm width respectively, as well as the length of the foot. (https://tutorial.xsens.com/video/body-measurements)

The inertial motion capture system is calibrated with the participant holding a neutral pose[10] such as an N-pose or T-pose, immediately followed by a walk calibration. The Xsens MVN software calculates the orientation of segments through the combination of individual IMU orientations with a biomechanical model of the human body. Each IMU orientation is achieved through the fusion of accelerometer, gyroscope and magnetometer signals using an extended Kalman filter[10,21]. The neutral pose assumptions from the sensor to segment calibration procedure derive the kinematics of 23 body segments[10]. Following this, the patient can undergo 3D motion analysis. This can involve walking at any desired gait speed (generally slow, self-selected and fast). The gait report will also calculate general parameters including the walking speed and cadence.

The MVN sensor fusion engine uses foot contacts to interact with the external world, by applying the biomechanical model in combination with advanced contact detection. The Xsens MVN gait report includes a contact event counter (Figure 9). Within the contact event counter, the foot strike section shows the number of foot strikes for each leg, as well as the foot release and indicates whether it occurred at the heel or toe. With standard healthy gait, the foot strikes will be seen as heel strikes, while the foot release will be seen as toe offs. Whereas a pathological condition such as foot drop may show some toe strikes in the foot strike section.

Contact event counter

Foot Strike

	Heel		Toe	
	n	%	n	%
Left	3	60.00	0	0.00
Right	2	40.00	0	0.00
Total	5	100.00	0	0.00

Foot Release

	Heel		Toe	
	n	%	n	%
Left	0	0.00	3	60.00
Right	0	0.00	2	40.00
Total	0	0.00	5	100.00

Figure 9: MVN gait report contact event counter

The gait report is stored in a secure cloud-based ecosystem. This has several advantages; file uploads allow the data to be processed without relying on front-end hardware. In addition to this, the cloud-based system, allows users with assigned permissions to access the reports from any location in a secure manner, improving communication amongst interdisciplinary teams. Each respective recording can then be selected with a gait report being prepared. The report contains general parameters, as well as each of the previously described spatial and temporal parameters, presented as means, standard deviations, and difference between left and right sides (Figure 10).

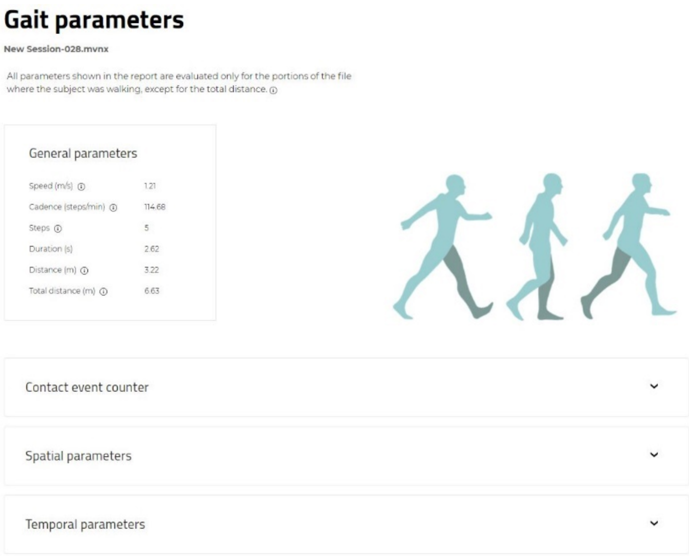
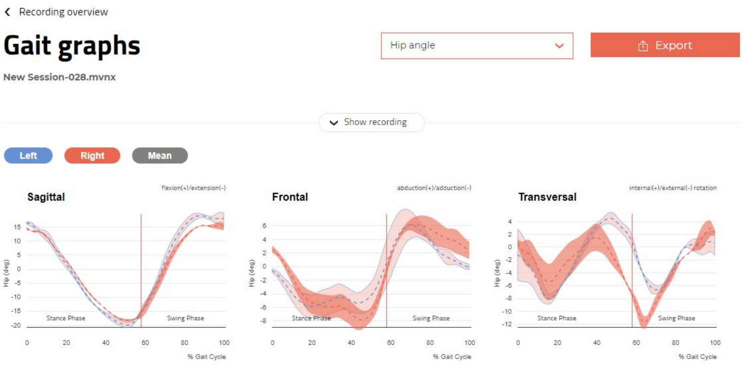


Figure 10: Gait parameters

The report also contains the gait graphs for each of the previously discussed joint angles and kinematics, with either each individual gait cycle plotted, or collectively as the mean ± standard deviation (Figure 11). Furthermore, the discrete values are extracted from the graphs, including the minimum and maximum for left and right, as well as the angle at foot strike and foot release.



Joint angle [deg]	Overall		Stance		Swing			
	Min	Max	Min	Max	Min	Max	At foot strike	At foot release
Left	-20.77	19.61	-20.77	16.70	-17.31	19.61	16.40 ± 0.41	-14.75 ± 0.89
Right	-18.83	16.31	-18.83	14.82	-17.05	16.31	14.37 ± 0.63	-15.06 ± 0.69
Difference	-1.94	3.31	-1.94	1.88	-0.26	3.31	2.03	0.31

*Direction of Progression

Figure 11: Gait graphs

3 Performance Analysis

In order to demonstrate the validity and performance of the MVN gait report. An experimental study was performed to compare the calculated spatial and temporal parameters with those that were measured by an optical motion capture system. The dataset was collected in an experiment performed at the University of Twente (ref); which consisted of a group of 35 healthy participants with a spread of age, gender, weight and height to give heterogeneity to the population. Participants were excluded if they suffered any pathologies or gait related limps, or needed a walking aid. Inertial data was captured using MVN Awinda, in which 8 of the 17 IMU units representing the motion of lower body plus sternum, was sampled at 100Hz in the *single-level* scenario. Synchronous to these inertial measurements, reflective marker based optical motion capture data was collected using a ten camera system (Vicon, Vicon Motion Systems Limited, Oxford), sampling at 100Hz along a ten-meter walkway, which included a force plate (AMTI OR6 Series force plate, Advances Mechanical Technology Inc). The objective of this dataset was to show the accuracy of spatial and temporal parameters measured using MVN Analyze, by comparing them with those obtained using Vicon's Plug-in Gait lower limb model. The Plug-in gait model consisted of sixteen reflective markers placed on appropriate bony anatomical landmarks[7].

Participants underwent data acquisition in a single session, in which three walking conditions were performed consecutively including their self-selected pace, a slow walk consisting of 60 beats per minute, and a fast walk consisting of 120 beats per minute. The Xsens data were processed using the Xsens Estimation Engine (XEE)[10] and subsequently exported to an MVNX file. This MVNX file was then uploaded to a Gait report, which created a gait report for each trial and walking condition. The synchronous data from the Vicon measurements were processed using the plug-in gait dynamic walking pipeline and subsequently exported to a C3D file. The Vicon Nexus Quick report was then used to create a gait report for each trial and walking condition. Validation was performed using the root-mean square error (RMSE) and Bland-Altman's limits of agreement for multiple measurements per participant. The following table presents the mean ± standard deviation (SD) for each of the spatial and temporal parameters calculated for self-selected walking, using both the Vicon gait report and Xsens gait report (Table 1). In addition to this, the bias ± SD, RMSE and upper/lower limits of agreement with 95% confidence interval is shown.

Upon analysis of the results, we observed relatively small errors in the spatial parameters of step length and stride length, with slightly larger errors in the step width. Across all spatial parameters, the negative bias observed indicates the Xsens' system slightly underestimated the spatial parameters. However, Bland-Altman analysis revealed overall, low biases and narrow limits of agreement, with exception of step width, which showed slightly wider limits of agreement. It should be noted, that step width showed non-normal distribution following Shapiro-Wilk normality testing, meaning the Bland-Altman analysis may not have been the most appropriate test. Non-parametric statistical methods could be further explored to analyse the non-normal distributed data.

Table 1

Parameters	Vicon mean±SD	Xsens mean±SD	Bias±SDdiff	RMSE	Lower LoA (95% CI)	Upper LoA (95% CI)
Step length left (cm)	68.49±7.49	67.02±6.81	-1.49±2.17	2.61	-8.00 (-9.03 - -6.98)	5.02 (4.00 - 6.05)
Step length right (cm)	68.89±6.68	67.60±6.68	-1.37±2.39	2.72	-8.03 (-9.18 - -6.89)	5.29 (4.15 - 6.43)
Step width left (cm)*	12.30±3.63	7.63±4.89	-4.67 ± 5.04	6.82	-15.20 (-17.96 - -2.43)	5.86 (3.10 - 8.63)
Step width right (cm)*	12.08±3.52	7.79±4.94	-4.29 ± 4.99	6.53	-14.81 (-17.54 - -2.08)	6.24 (3.514 - 8.96)
Stride length left (cm)	136.93±13.38	134.87±12.41	-2.15±2.63	3.36	-9.64 (-10.90 - -8.40)	5.35 (4.10 - 6.60)
Stride length right (cm)	137.16±13.47	134.78±12.47	-2.47±2.55	3.52	-9.62 (-10.84 - -8.40)	4.68 (3.46 - 5.90)
Single support left (s)	0.41±0.03	0.46±0.04	0.06±0.03	0.06	-0.00 (-0.02 - 0.01)	0.12 (0.11 - 0.13)
Single support right(s)	0.41±0.03	0.47±0.05	0.06±0.03	0.07	-0.00 (-0.02 - 0.01)	0.13 (0.12 - 0.15)
Single support left (%)	37.68±1.77	43.13±2.74	5.47±2.19	5.88	0.32 (-0.81 - 1.44)	10.63 (9.51 - 11.75)
Single support right (%)	37.42±2.03	43.65±3.00	6.29±2.56	6.77	0.42 (-0.91 - 1.75)	12.16 (10.83 - 13.49)
Double support left (s)	0.26±0.04	0.07±0.03	-0.19±0.04	0.20	-0.28 (-0.30 - -0.26)	-0.11 (-0.13 - -0.09)
Double support right (s)	0.27±0.04	0.08±0.03	-0.19±0.04	0.19	-0.27 (-0.29 - -0.25)	-0.11 (-0.13 - -0.09)
Double support left (%)	24.29±3.18	6.32±2.56	-18.05±3.20	18.32	-25.32 (-26.99 - -3.64)	-10.78 (-12.46 - -9.10)
Double support right (%)	24.52±2.97	7.06±2.66	-17.51±3.04	17.76	-24.22 (-25.83 - -2.60)	-10.80 (-12.42 - -9.19)

* Indicates non-normal distributed data

The temporal parameters appeared to perform well with respect to single support with low errors, low bias and narrow limits of agreement. However, double support was found to show larger biases and wider limits of agreement, with Xsens slightly underestimating the time in both seconds and percentage. The addition of both left and right double support time comes close to the 20% that occurs in gait, with faster walking speeds lowering this value[1]. Previous studies using inertial measurement units to investigate spatiotemporal parameters have also found that temporal parameters and parameters dependant on the spatial information of one foot have shown lower relative RMSE when compared to those that require information of two feet[22]. Summarising the temporal parameters describing two feet and describing the lateral distance between them may need further improvement. However, collectively these results are still encouraging with respect to its validation in clinical settings.

Whilst this dataset only presents the data of spatial and temporal parameters against the Plug-in Gait report of Vicon. It is worth noting that the reporting of kinematic joint angles described earlier in this paper, gives valuable insight into the functional contributions of each joint towards gait. Previous studies have validated the Xsens MVN system in the reporting of joint angles, against more advanced marker sets during gait[11,13] and daily living activities[12]. Karatsidis et al (2018) has shown excellent accuracy of lower limb joint angle estimation during gait across slow, self-selected and fast walking speeds. Furthermore, Konrath et al. (2019) demonstrated excellent accuracy of lower limb joint angle estimation during walking, stair ascent, stair descent and sit to stand activities. It is worth noting, the findings of this potential dataset apply to normal gait, and examining subjects with potential gait impairment should understand the present limitations with inertial motion capture methodology including the need for appropriate joint alignment in sensor to segment calibration. Additionally, the definition of an acceptable level of resolution should be further discussed with respect to each of the spatial and temporal parameters from a clinical context.

4 Conclusion

In this whitepaper, the newly released Xsens MVN gait report is presented as a tool to reduce the costs associated with clinical gait analysis, as well as improve its adoption within the clinical community. Further, the cloud-based system allows users to access the reports in a secure manner, improving the communication amongst interdisciplinary teams. The performance of the spatial and temporal parameters was compared against a reference based on optical data. Overall, the data showed encouraging results across a wide range of clinically relevant parameters, with only step width and double support time needing potential improvement. The Xsens Motion Cloud gait report enables rich quantitative data in the form of joint angles, segment kinematics, centre of mass tracking, and foot contacts, which allow many gait properties of interest to be investigated and improved clinical care.

5 References

1. Richards, J. *Biomechanics in clinic and research*. (Churchill Livingstone, 2008).
2. Novacheck, T. F. The biomechanics of running. *Gait Posture* **7**, 77–95 (1998).
3. Cappozzo, A., Catani, F., Della Croce, U. & Leardini, A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin. Biomech.* **10**, 171–178 (1995).
4. Zatsiorsky, V. M. Kinematics of human motion, Human Kinetics. *Urbana Champaign* (1998).
5. Delp, S. L. *et al.* OpenSim: Open source to create and analyze dynamic simulations of movement. *IEEE Trans. Biomed. Eng.* **54**, 1940–1950 (2007).
6. Damsgaard, M., Rasmussen, J., Christensen, S. T., Surma, E. & de Zee, M. Analysis of musculoskeletal systems in the AnyBody Modeling System. *Simul. Model. Pract. Theory* **14**, 1100–1111 (2006).
7. Kainz, H. *et al.* Joint kinematic calculation based on clinical direct kinematic versus inverse kinematic gait models. *J. Biomech.* **49**, 1658–1669 (2016).
8. Andersen, M. S., Damsgaard, M. & Rasmussen, J. Kinematic analysis of over-determinate biomechanical systems. *Comput. Methods Biomech. Biomed. Engin.* **12**, 371–384 (2009).
9. Schepers, H. M., Koopman, H. F. J. M. & Veltink, P. H. Ambulatory assessment of ankle and foot dynamics. *IEEE Trans. Biomed. Eng.* **54**, 895–902 (2007).
10. Schepers, M., Giuberti, M., Bellusci, G. & others. Xsens mvn: Consistent tracking of human motion using inertial sensing. *Xsens Technol.* 1–8 (2018).
11. Karatsidis, A. *et al.* Estimation of ground reaction forces and moments during gait using only inertial motion capture. *Sensors* **17**, 75 (2016).
12. Konrath, J. M. *et al.* Estimation of the knee adduction moment and joint contact force during daily living activities using inertial motion capture. *Sensors* **19**, 1681 (2019).
13. Karatsidis, A. *et al.* Musculoskeletal model-based inverse dynamic analysis under ambulatory conditions using inertial motion capture. *Med. Eng. Phys.* **65**, 68–77 (2019).
14. Alamdari, A. & Krovi, V. N. A review of computational musculoskeletal analysis of human lower extremities. in *Human Modelling for Bio-Inspired Robotics* 37–73 (Elsevier, 2017).
15. Bertoli, M. *et al.* Estimation of spatio-temporal parameters of gait from magneto-inertial measurement units: multicenter validation among Parkinson, mildly cognitively impaired and healthy older adults. *Biomed. Eng. Online* **17**, 58 (2018).
16. Andriacchi, T. P. & Dyrby, C. O. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. *J. Biomech.* **38**, 293–298 (2005).
17. Nester, C. J., Van Der Linden, M. L. & Bowker, P. Effect of foot orthoses on the kinematics and kinetics of normal walking gait. *Gait Posture* **17**, 180–187 (2003).
18. Karatsidis, A. *et al.* Validation of wearable visual feedback for retraining foot progression angle using inertial sensors and an augmented reality headset. *J. Neuroeng. Rehabil.* **15**, 78 (2018).
19. Gordon, K. E., Ferris, D. P. & Kuo, A. D. Metabolic and mechanical energy costs of reducing vertical center of mass movement during gait. *Arch. Phys. Med. Rehabil.* **90**, 136–144 (2009).
20. Chastan, N. *et al.* Influence of sensory inputs and motor demands on the control of the centre of mass velocity during gait initiation in humans. *Neurosci. Lett.* **469**, 400–404 (2010).
21. Paulich, M., Schepers, M., Rudigkeit, N. & Bellusci, G. Xsens MTw Awinda: Miniature wireless inertial-magnetic motion tracker for highly accurate 3D kinematic applications. *Xsens: Enschede, The Netherlands* (2018).
22. Teufl, W., Miezal, M., Taetz, B., Fröhlich, M. & Bleser, G. Validity of inertial sensor based 3D joint kinematics of static and dynamic sport and physiotherapy specific movements. *PLoS One* **14**, e0213064 (2019).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