Kinematic measurements for the characterization of the dynamics of hopping

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Abstract. The study of human movement requires the accurate measurement of the forces and of the kinematic quantities involved. Here we consider hopping, that deserves great attention in the literature, since it combines the activation of a complex sensorimotor control with the relative simplicity of the gesture. The movement of the center of mass and the contact conditions are of special interest. Thus a measuring system that combines digital image acquisition, force measurement based on a force plate and extensive use of inertial sensors, for linear and rotational motion, has been developed and characterized. The results concerning the accurate measurement of contact conditions are specially outlined.

1. Introduction
Hopping is widely considered as a reference gesture when studying lower limb mechanical behavior [1-6]. The gesture is mainly bidimensional, with dominant movements in the sagittal plane. Repeatability and reproducibility can be improved by controlling the hopping rate. Preliminary studies have defined a preferred frequency for humans so the gesture can be repeated at this frequency with the help of a metronome [1]. A satisfactory representation of the gesture can be obtained by a model of the whole body, specifically of the lower limbs, consisting of rigid elements [1,2,3]. Related measurements involve both kinematic and dynamic quantities. Several dynamic issues are involved in hopping, such as the ground reaction force and its relationship with centre-of-mass acceleration, the elastic contribution of the lower limbs and the behaviour of the moment they express, as a function of position or angles. In this paper we are mainly interested in kinematic quantities since they are directly involved in the asset control required to maintain a macroscopic constant position of the body in the sagittal plane, during the performance [8]. In this scenario, among all kinematic quantities, we focus mainly on two: the centre of mass (CM) of the whole body and the point where the forces and moments are exchanged through the feet with the floor (Centre of Pressure, COP). Generally the quality and reliability of the measurement result is taken as grated, while some attention is given to the processing algorithms [7]. This paper presents a measurement system designed to obtain reliable measurement results for a set of kinematic and dynamic quantities, based on a video system operating with markers, inertial sensors and a force platform. The kinematic of the lower limbs may be obtained from two independent methods, so it is possible to provide a result verification by comparison of the two measurement results. The positions of the points of interest on the sagittal plane can be obtained directly from video or force data, or they can be evaluated...
through the use of a rigid model of the limb, by using the inertial data [9]. In the paper we will present the measurement system in detail, including the processing of the measurement signals; we will introduce an experimental procedure that enables the evaluation of repeatability and reproducibility of the gesture and finally discuss the measurement results with particular focus on kinematic data for the CM and COP and their verification.

2. The gesture and its model
Hopping is an interesting gesture from the biomechanical point of view since it provides a large amount of information about the lower limbs behaviour, under natural, relaxed, conditions or when the task requires a higher level of performance. Beside that, since the hopping is performed on site, with rather small body displacements in the horizontal plane, it presents interesting biomechanical aspects as regards the position control required to maintain the equilibrium in a fairly constant horizontal position, while hopping and moving the whole body in the vertical direction. In literature some studies about the dynamics of hopping are available. They are mainly focused on dynamics aspects combining kinematic and force data to evaluate the moment required and the limbs joints, studying the adjustment of the lower limbs behaviour, according to the required performance, or due to the geometric nature of the ground, such as flat, inclined or uneven, or to ground’s dynamic nature such as rigid or compliant. Rarely the kinematics of the CM and COP are deeply investigated. In this case our interest is to develop a model of an hopping man, considering a schematization of lower limb behaviour, but introducing also the problem of stability, so considering the whole body behaviour. Of course such a model has to be based on reliable experimental kinematic data. As regards the measurement problem, hopping is rather favourable since, on one hand it is a simple gesture occurring, in first approximation, in the sagittal plane, on the other it offers the possibility to carry on repeated and reproducible measurements. The former aspect influences the hardware set up that is simpler as compared with three dimensional gestures, while the latter enables measurement procedures including estimation of repeatability and reproducibility uncertainties.
Hopping frequency may vary according to the task required, such as maximum height or test duration. In our case the subject is required to hop at a fixed frequency of 2.2Hz, as presented by a metronome. Such frequency corresponds to the expected hopping frequency when a natural task is required, without particular effort or performance [1]. Each subject has to perform at least two sets of tests: hopping naturally and at maximum height [6] maintaining in both cases the same pace as suggested by the metronome.

3. The measurement system

The measurement setup is presented in figure 1. The video system is based on a BASLER camera (details in table 1) connected via IEEE1394. Optics has been selected to have a complete view of the subject during hopping, considering also the maximum height case. Active markers consisting in high intensity white led, are sewn on an elastic running suit. Subject performing the test wears the instrumented suit and markers are adjusted in proper positions.

| Table 1. Camera technical details. |
|-----------------------------------|
| Resolution | 640 (vertical) x 480 (horizontal) |
| Pixel size | 9.9 µm x 9.9 µm |
| Sensor dimension | 1/2 in |
| Maximum frame rate | 60 Hz |
| Optics | 16mm C mount |

The subject is instrumented also with 5 inertial sensors (Inertial Motion Unit, IMU) from Xsens Technology placed on limb’s segments and torso. Each unit is equipped with triaxial accelerometer, gyroscope and magnetometer and wireless connected to a base station, some technical details are available in table 2. IMU signals are internally pre-processed by Xsens software, obtaining as a result the three orientation angles in the space for each unit, together with acceleration data. Synchronization between frame acquisition, force data acquisition and IMU sensors is made possible by acquiring a synch signal from the IMU base station. The synch signal enables off line time synchronization of all the data.

| Table 2. IMU - Xsens MTW - technical specifications. |
|--------------------------------------------------------|
| Dynamic range | ± 200 °/s, ± 160 m/s² |
| Static accuracy (roll-pitch) | <0.5 ° |
| Static accuracy (yaw) | 1 ° |
| Angular resolution | 0.5 ° |
| Internal sampling rate | 1800 Hz |
| Bandwidth | >120 Hz |
| Wireless sampling rate (6 sensors) | 75 Hz |

After camera calibration, during video capture, optics diaphragm is closed, to obtain dark images with light markers, then a threshold is applied to obtain black or white (binary) pixels in each frame. The position on the image of the white spots, corresponding to each marker, is computed and converted in positions by using the calibration constant, determined, for the specific set up, before and after each test.
4. Data processing
Markers and IMU sensors are placed on the leg facing the line of view of the camera, as presented in table 3. By processing position data it is possible to obtain either segment angles in the sagittal plane, or, with the support of a simple rigid model of the lower limbs and torso, segment extremities positions. In both cases these data can be compared with IMU measurement values, validating the experimental results.

Table 3. marker positions definition.

| marker | position | foot | ankle | tibia | knee | femur | hip | shoulder |
|--------|----------|------|-------|-------|------|-------|-----|----------|
| 1-3    |          |      |       |       |      |       |     |          |
| 4      |          |      |       |       |      |       |     |          |
| 5-6    |          |      |       |       |      |       |     |          |
| 7      |          |      |       |       |      |       |     |          |
| 8-9    |          |      |       |       |      |       |     |          |
| 10     |          |      |       |       |      |       |     |          |
| 11     |          |      |       |       |      |       |     |          |

Center of mass position in the sagittal plane is measured considering the position of the marker corresponding the iliac crest, that is located at about the same height from the ground of the center of mass of the whole body, or it is calculated on the basis of a rigid segment model of the lower limb and torso, considering the measurement of the orientation of each segment. Center of pressure is defined as the point, in the transversal plane, where the overall force is exchanged with the ground. It’s position can be determined considering the force data from the platform. It can be interesting the measurement of the contact point also, the point around which the foot rotates during contact, due to the movement of the ankle. As for the COM, it can be estimated using video system (markers located on the heel, malleolus and metacarpus) or considering the IMU data in the hypothesis of a foot consisting of two rigid parts articulated in the metacarpus.

5. Measurement procedure
To guarantee results reproducibility we have developed a detailed measurement procedure. The video system is calibrated using a vertical reference with marks every 100 mm located at the same distance from the camera of the instrumented right hand side of the subject, before and after the hopping test. Generally we obtained a resolution of about 3.2 mm/pixel, differences between before and after the test were below the resolution of the system and even the reproducibility due to different measurement setup was very low and less than 0.2 %. In order to compare video and COP data, it is necessary to calibrate the systems together. We have proceeded recording force and video data with a 20 kg weight placed in the center of the force platform and at a known distance from it. By processing force data it is possible to measure the COP due to the weight and compare its position in frontal direction with the one obtainable from the video. In such a way video and COP measurements in the frontal direction refers both to the same origin.

IMU sensors are placed near the test site and, after activation, they rest quiet for at least one minute of warm up, while stability of the readings is verified. Subject wears the instrumented running suit and IMU sensors are placed on site by using elastic straps. Markers positions are finely adjusted in the reference points as in table 3. Before and after the hopping the subject stands still in front of the camera and a complete still measurement of about 45 s is performed. The hopping test is performed with a reference sound giving the 2.2 Hz pace. The test starts when the subject feels a good accordance with the pace, and it lasts for at least 10-15 s, then the subject rest for some time, while data are checked. The experimental session consists of several test at both normal and high height, and it ends with a static recording. After the test all the measurement data are verified and if they present inconsistencies, such as large differences between the two calibrations or the two still measurements, rhythm anomalies and so on, the hopping test is discarded.
6. Preliminary experimental results
The measurement system is still under development, in particular as regards the video acquisition system, since we are going to use a higher resolution and higher speed camera, nevertheless we can present here an example of the obtainable results, demonstrating the measurement system potentialities and some of the difficulties we are going to face in such kind of measurements. Figures refer to hopping tests, performed by a 65 kg, 1.72 m, male subject.

![Figure 2. GRF for normal height, 2.2 Hz hopping.](image1)

![Figure 3. Angles movements for the leg and torso.](image2)

Figures 2 and 3 presents the time histories of the ground reaction force (GRF) and of the angles involved in the gesture, for a subset of hops in the same test: the good repeatability is apparent. A reference contact signal may be obtained by thresholding the Ground Reaction Force signal. It is now possible to analyse values of interest at touchdown and their variations during the contact phase as presented in table 4, together with some reference values from the literature [2].

| Table 4. Experimental results. Mean values and standard deviation of the measurements in multiple tests. Literature references from [2]. |
|---------------------------------------------------------------|
| **Quantity** | **Normal height** | **Maximum height** |
| | **Experiment** | **σ** | **Liter.** | **Experiment** | **σ** | **Liter.** |
| Hopping rate | 2.2 Hz | 1.7% | | 2.2 Hz | 2% | |
| time spent at ground | 260 ms | 9 ms | 308 ms | 198 ms | 9 ms | 260 ms |
| Ground reaction Force | 2180 N | 3.6% | 1740 N | 2800 N | 3.6% | 2179 N |
| Touchdown angles [deg] | | | | | | |
| Hip | 172 | 1 | 171 | 175 | 2 | 173 |
| Knee | 160 | 2 | 150 | 160 | 2 | 154 |
| Ankle | 126 | 2 | 125 | 126 | 2 | 130 |
| Excursions at ground [deg] | | | | | | |
| hip | 10 | 1 | 10 | 8 | 1 | 3 |
| Knee | 24 | 2 | 23 | 23 | 2 | 13 |
| Ankle | 39 | 2 | 32 | 40 | 3 | 26 |
Mean values show a rather good agreement with literature values considering that results from this study refers to several tests by a single subject while in the literature case a set of subjects was considered, and it had balanced gender and age composition. Beside that it is worth noting that absolute angles depends on marker alignment on the subject’s limb.

Moving now to the main aim of this study we consider frontal movements of the center of mass (CM) of the whole body and of the center of pressure, COP. The CM position may be measured through the markers data, considering that it is about 15 cm above the hip marker. Otherwise its position can be evaluated considering the CM of each body segment and its position in the space. This second procedure may use marker video data, or orientation data from the inertial sensors, and it is still under development. Figures 3 presents a time history data for the frontal movement in the sagittal plane of the hip marker, the foot markers, the COP and the center of mass of the whole body, together with the contact signal.

We can briefly discuss this graph considering that since the CM is located above the hip marker, and the torso is a bit inclined and not fully upright, the CM position is a bit displaced from the hip. From a dynamical point of view the COP at touchdown tends to the back and returns in the front of the foot, while the CM present a smoother behaviour in accordance with the COP.

![Figure 4. Frontal movements of COP, CM and other keypoints during the contact phase.](image)

In the study of the contact phase, in addition to the points previously described, the instantaneous centre of rotation (CR) plays an important role. Generally it is assumed to be coincident with foot metacarpus, but of course it is interesting to measure its position. This rather complex goal can be archived assuming foot top as a rigid element and considering velocity vectors measured at malleolus and metacarpus markers. Since we are considering a rotation of a rigid segment, at every instant the two straight lines by the extremes of the velocity vectors intersect in the instantaneous centre of rotation. Considering marker positions direct measurements we have developed an indirect CR measurement procedure that is currently under validation.

The reliability of the measurement results depends on several influence quantities related to both the measurement system and the measurand itself. In the particular case of the tests we
have presented here, we had good repeatability and reproducibility but they also depend on subject performance, that, if necessary can be improved by training. At the interface between the measurand, or the subject performing the gesture, and the measurement system, there are markers and IMU sensors. It is possible to validate the results by comparing the angles as measured by IMU or from markers’ positions, as presented in the following figure 5. The limited differences between them is on one side a validation of the results, on the other it might be due to a slight misalignment between the sagittal plane, assumed coincident with the plane of the image, and the IMU coordinate system. Another validation possibility is to verify the length of body segments that can be assumed as rigid. Figure 6 presents the femur and tibiae lengths as a function of time during the hopping. Segments’ lengths are evaluated considering the markers distance between malleolus and knee (tibiae) and between knee and hip (femur). They are not rigourously constant, probably because markers move from their reference positions during performance. Markers are sewed to the elastic fabric adherent to the subject’s leg with the help of some elastic tape also. Nevertheless, during the performance, due to movements mainly at ankle and knee and to muscular activation, they move causing a segment length variation. This is a typical problem in biomechanics, but both the rather small variation in segment length which is less than 1.5 % for tibiae, the worst case, and the good agreement on the angles computed from video and inertial data gives confidence to the reliability of the results.

![Figure 5. Knee angle as measured by video and IMU systems.](image1)

![Figure 6. Tibiae and femur segments’ lengths.](image2)

7. Conclusions
We have presented a redundant measurement system for the kinematic characterization of hopping. Several studies of this gesture are available in literature, mainly focused on the general dynamics of lower limbs. To understand the dynamics of hopping it is necessary to better characterise the contact conditions through proper kinematics quantities, than currently available in the literature.

A combination of marker, video and inertial sensors was used to get the possibility to validate the results by comparison and internal validation. In this case our interest was mainly focused on the contact phase characterised by the center of pressure, the center of mass of body segments and whole body, the foot position and its instantaneous center of rotation.

The paper presents and discusses some measurement results which are in accordance with the available results in literature, show good repeatability and reproducibility and can be verified by comparison between different measurement methods. Nevertheless results present some
measurement problems that emphasize the common difficulties to be faced when dealing with measurements in biomechanics. In this particular situation the possibility to cross validate the results obtained from different measuring methods is a useful opportunity.

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