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MEASUREMENT SET UP FOR THE EXPERIMENTAL STUDY OF THE DYNAMICS OF HOPPING

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Abstract – Hopping is a gesture that, though simple, is apt to providing precious information on human-body dynamics, including dynamic stability. Currently available studies are normally based on a limited set of sensors and scarcely provide metrological details. This paper presents a new multi-sensors measurement set-up, including acceleration, force, angles and image-based positions. The metrological characteristics of the system are discussed, including systematic and random uncertainty contributions, measurement conditions and procedure. The same experimental apparatus may be used for studying other motion gestures, such as stepping down, forced hopping or cycling, thus providing a flexible experimental tool.

Keywords: human motion, sensors, measurement of human functions

1. INTRODUCTION

Hopping is a simple biomechanical gesture whose study provides important information on leg dynamics, useful in diagnostics, sport biomechanics, prosthesis development and rehabilitation. Available studies [1-4] mainly discuss modelling issues and legs stiffness [5-6]. Experimental studies are in general based on vision systems and the measurements of ground reaction force.

The proposed models often give information regarding the acceleration of the legs' segments but specific measurements of such kinematics quantities are scarcely considered. Furthermore, no redundancy is provided to validate the measurements and to guarantee their reliability. The lack of a metrological characterisation of the measurement systems do not permit the evaluation of uncertainty and the quantitative assessment of the concordance between model and experiment.

This paper presents a measurement set up which integrates several sensors for different quantities, enabling both a detailed analysis of the gesture and a validation of the measurement results. The measurement system is described in detail and its performance is discussed with emphasis on the reliability of the results. The measurement procedure for the hopping is presented with some preliminary experimental results to give an idea of the amount of information that it is possible to retrieve from the system. Some open issues and future development of both the measurement hardware and data processing software are described. The system is based on measurements of acceleration, ground reaction force kinematical quantities relative to various leg segments, including relative angles, carried out by a vision system and by micro-electromechanical sensors (MEMS).

2. EXPEIRMENTAL SET UP

Measurement systems used in biomechanics for motion analysis are mainly based upon video tracking systems. Sometimes force measurements are also implemented through mono-axial or tri-axial force platforms. Rarely other sensors are used and application of video and force systems together are not so common. Moreover, in literature it is possible to find a detailed characterisation of the measurement data variability due to the difference performances of the same or different subjects, but very few indications regarding the metrological characterisation of the measurement system.

The proposed approach aims to a complete, detailed and possibly redundant characterisation of the movement and thus requires the implementation of a set of sensors for the measurement of different quantities characterising the body behaviour during the gesture. Redundancy offers the possibility to validate the measurement data and the procedure for example by comparing results from different sensors after proper processing.

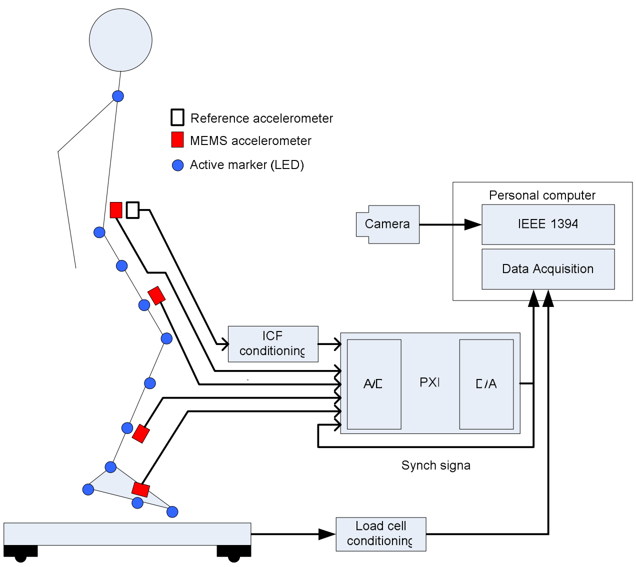


Figure 1 Overall scheme of the measurement system

The measuring set up has been designed to measure mainly the biomechanics of the leg's segments, but it can be extended to other parts of the body.

The measurement system is based upon

- video measurements of the positions of a set of markers properly placed on the body,
- acceleration measurements of the leg segments,
- acceleration measurements of a point near the centre of mass of the body and
- ground reaction force measurements.

Figure 1 presents a scheme of the overall set up, to be described in the following.

2.1. Video measurements

Since one of the goals was the characterisation of the leg mechanics during the gesture, the main set of interesting points is related to leg's joints: hip, knee and ankle. The motion takes place in the sagittal plane, so a 2D system is fit to purpose and the subject will be instrumented only on the side facing the camera. Since the leg's segment reconstruction may be difficult with only two points on each segment, some extra markers are positioned in the first and second segment. Beside that, an extra point is needed to verify the small movements of the trunk. The overall set of eleven, markers is reported in table 1.

Markers are realised with 3mm diameter , high intensity white LEDs. Most important issues in selecting the proper light source are: -the intensity, to be able to carry out the measurement in a daylight environment maintaining a good contrast between dark background and the shining markers; - the light cone angle to be wide enough to be able to record marker positions even if a small rotation happened for some reason. The actual solution are 25° emission, white LEDs with a 5000 mcd intensity.

A Basler A 601camera with an IEEE-1394 interface is used to video record the markers position in the saggital plane with a resolution of 640x480 pixels at about 20 frame/s. The camera is acquired by a LabView® program managing also the data acquisition from the platform load cells. The video frame rate is sufficient to monitor the hop in the place gesture paced at a fixed frequency of 2.2Hz.

Table 1 Marker and sensors position

Position	Video	Sensors
Tiptoe	Marker 1	
Metatarsus	Marker 2	A4 - ADXL 250 X-Y
Heel	Marker 3	
Ankle	Marker 4	
Tibia 1	Marker 5	A3 – ADXL 250 X-Y
Tibia 2	Marker 6	
Knee	Marker 7	
Femur 1	Marker8	A2 - ADXL 250 X-Y
Femur 2	Marker 9	
Hip	Marker 10	
Iliac crest Centre of Gravity		A1 - ADXL 250 X-Y A0 - B&K 4507
Shoulder	Marker 11	

2.2. Acceleration measurements

Acceleration measurements in biomechanics present several difficulties mainly due to the sensor positioning and installation on the subject and to the physical significance of the measured quantity. In this sense small, lightweight and flat shaped sensors may help in limiting disturbing effects such as the oscillation of the sensor itself and of the wobbling masses due to the soft tissues between the sensors and the bone [16].

In this application we are using two axis MEMS accelerometers by Analog Device, ADXL250 model, together with a Bruel&Kjaer 4507 mono-axial accelerometer as a reference sensor, mounted, with a proper adaptor, near one of the MEMS devices on the iliac crest [1]. MEMS sensors do not require any conditioning, while 4507 has standard ICP conditioning by a B&K Nexus system.

MEMS devices are based on capacitance principle and have the advantage to be able to measure the static gravity acceleration also, enabling the measurement of their orientation in the gravitational field. They are very lightweight and flat in shape so they can be face to the skin minimising inertial problems. MEMS sensitivity and zero bias specifications have large tolerances so a preliminary calibration is required. We have performed both a static and a dynamic calibration. Static calibration was carried out using the gravitational field in the laboratory by orienting the sensors at known angles. Main results regards the calibration curve including linearity, sensitivity and zero bias. The dynamic behaviour was obtained with an electrodynamic shaker by varying the excitation frequency and comparing the output with a wide bandwidth reference accelerometer. The MEMS frequency response resulted flat in modulus with a 10% tolerance up to about 1kHz depending on the sensor: wide enough for our application.

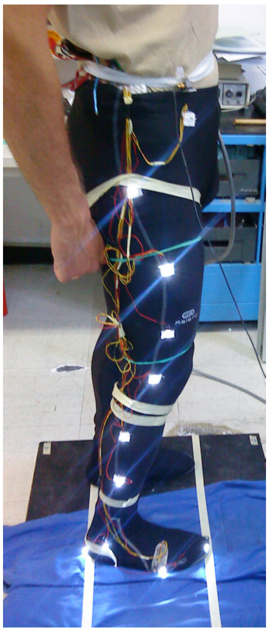


Fig. 2. a subject wearing the instrumented pants

2.3. Sensor positioning

Due to the large number of markers and sensors involved, an important issue was the possibility to set up the system in an easy, fast and reproducible way. So markers and sensors to be positioned on the legs were inserted in a pair of running pants, as shown in figure 2. Both the fixation and the pants elasticity guarantee that when pants are worn sensors assume a stable position pressed on the legs.

2.4. Force measurements

A force platform has been designed and developed based upon a set of four strain gage load cells placed on a rigid structure. Load cells with a range of 2500N are conditioned by a National Instruments module taking care of the power supply, signal amplification and filtering. The rigidity of the frame has been verified by a finite element analysis. The static and dynamic behaviour were investigated by placing a known mass in known points on the rigid structure and by the use of an instrumented hammer [10-14]. In this case, due to the sensors used, the frequency response is rather limited, rising up to 100Hz. Even if this could be sufficient for the study of the hopping in the place with a fixed frequency set to 2.2Hz, the system might be too slow for other gestures, for example for the study of single hopping at maximum height.

2.5. Data acquisition system

The data and video acquisition system has to manage 9 acceleration signals and four load cells signals acquired at 2 kHz sampling frequency, and a video acquisition at about 20 frame/s, synchronised with data acquisition.

This duty is rather heavy, mainly as regards memory access. For this reason we have designed the system with two independent but synchronized computers, managing acceleration one side and force and video signals on the other. An overall scheme is presented in figure 1.

A personal computer with a National Instrument data acquisition PCI device and a IEEE 1394 interface is used together with a PXI data acquisition system.

Synchronisation is obtained through the generation of a train of pulses from one system that is forwarded and recorded by both data acquisition systems. Off line it is possible to synchronise automatically the three recordings (acceleration, force and video) as described later on. The video and data synchronisation is obtained in the LabVIEW program, by recording the delay when reading the data from the acquisition device.

3. MEASUREMENT PROCEDURE

The measurement procedure requires several steps in order to guarantee a reliable result. In the following some details are given on main topics.

3.1. Video system calibration

The camera is mounted on a tripod with a 12mm C-mount optics, with the wider side in the vertical direction in order to maximise the resolution. A preliminary alignment is required to set the parallelism of the sensor plane to the vertical one. Then a 1.2 m ruler with ticks every 100mm is placed in the vertical direction, on the platform in correspondence of the instrumented side of the subject and a picture is saved. Later on the calibration will proceed by detecting the ticks at known distances in the recorded image, to evaluate the spatial sensitivity of the system [9]. In this set up we have found values of about 3mm/pixel.

3.2. Gesture definition and subject training

The biomechanical gesture under investigation has to be clearly defined and explained to the subject. In our case in order to minimize the variability causes a reference frequency is reproduced with an audio system in ortder to give the proper rhythm to the subject. Some training before the measurement campaign may be required. After havine worn the instrumented pants a check of the alignment of the markers on the leg is necessary together with the positioning of the marker on the shoulder.

3.3. Data acquisition and processing

Each recording lasts about 10 to 30 s including a set of 20-60 hops, and generates 3 data files with acceleration, force and video data. The data processing takes place off line and it requires video processing and force and acceleration synchronisation, before analysing the measurement signals.

Video processing requires first of all the image binarisation in order to have a black image with white markers. Then the code looks for the centre of the white dots, that in general are up to 3 pixels wide. Marker coordinates in the plane of the image are saved in a separate file that contains all the information available in the video file. Force and acceleration data are acquired on different systems, so it is necessary to synchronise them. This is possible by considering the first rising edge of the train of pulses acquired by both the systems. In this way the maximum phase difference is a sampling period, equal in this case to 0.5ms, few enough for our purposes. Of course more sophisticated algorithms may be implemented reducing this phase delay.

The analysis of the measurement signals may start with the validation of the measurements. Having a sensor redundancy, several possibilities are available, for example:

- accelerations from the MEMS sensor at the centre of mass may be cross checked with the acceleration at the same point measured by the reference accelerometer;
- markers positions may be compared with the double integration of the accelerometers signals;
- the length of the legs segments should be as constant as possible, any change can be due to markers movements on the leg;
- markers coordinates may be affected by the movements of the subject going away or near the camera, altering the calibration constant. This can be controlled by checking the coordinates of the centre of force as measured by the force platform. In our case the movement during a series of subsequent hops is of the order of some millimetres [15].

After validation the analysis of the biomechanics of the gesture can proceed analysing all the available information. Some examples are given in the analysis of the test case.

4. EXPERIMENTAL RESULTS

We are planning to use the described measuring set up, to characterise the hopping in the place gesture, analysing the motion of several subjects performing natural and forced hopping several times to be able to evaluate intra and inter subject variabilities.

In the following we present some preliminary experimental results regarding natural hopping of one subject having 71 kg mass. The frequency of hopping was timed by an acoustic signal beeping at 2.2 Hz [1].

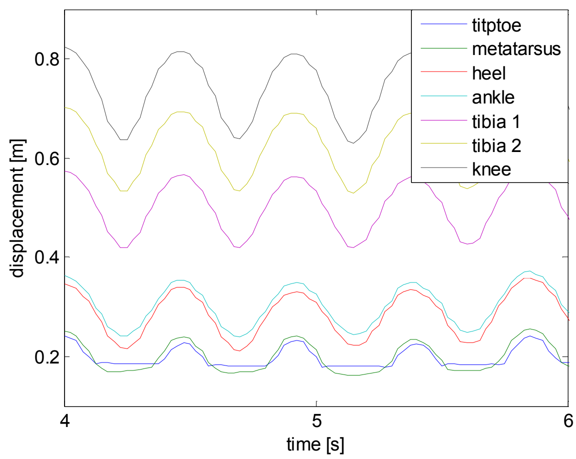
The vertical movements of all the markers are presented in figure 3a and b. Note that on the two leg segments there are 4 markers with one point in common at the knee. In future we plan to use all the information to compute the best fit lines for the two segments, obtaining a more accurate evaluation of the position of the centre of mass of each segment and of the knee as the intersection between the two virtual segments.

Figure 4 presents the movement in the vertical plane for two particular markers: the hip that is roughly positioned at the height of the centre of mass of the body and of the knee. Note the almost vertical motion of the hip in comparison with the motion in the plane of the knee.

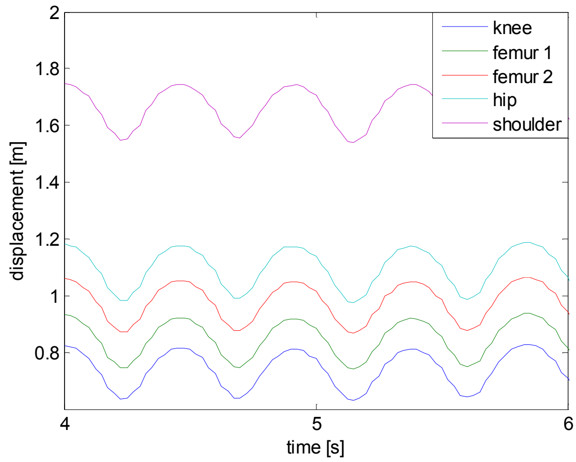
Figure 5 presents vertical acceleration at the iliac crest as measured by the reference and the MEMS accelerometers. Peaks are in correspondence with the periods of ground contact. The signals are very similar and shows differences at the peak levels indicating possible mounting effects of the reference accelerometer. During flight periods the MEMS sensor is able to properly detect gravity, while the AC response of the piezoelectric reference accelerometer gives a less clear signal.

Figure 6 presents the force as measured by the force platform. A contact signal determining if the subject is on the ground or flying can be obtained from the force by introducing a proper threshold.

A good description of the legs movement can be obtained considering the angles at the knee and at the ankle.

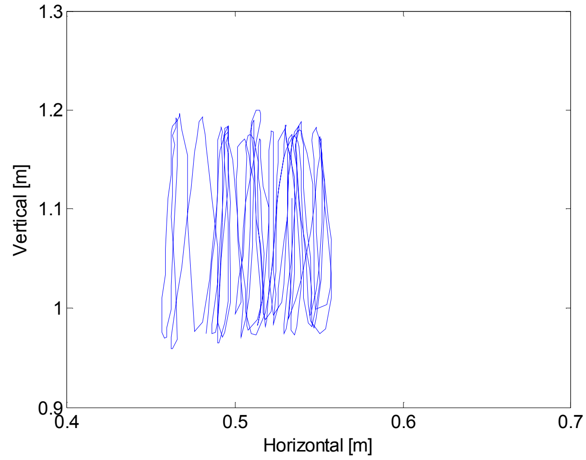


(a)

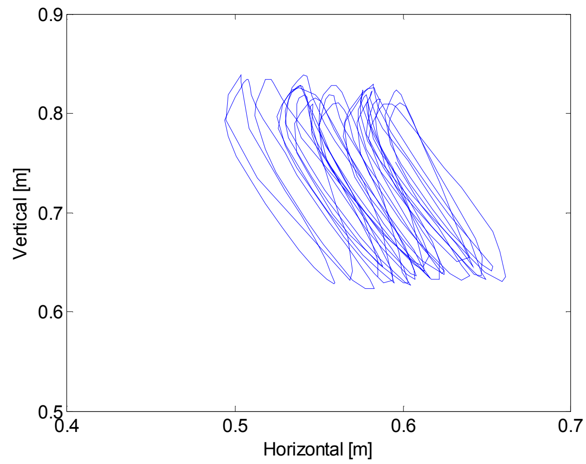


(b)

Fig. 3. Vertical movements of the 11 makers: 3a movements from tiptoe to knee; 3b from knee to shoulder.



(a)



(b)

Fig. 4. Movements in the vertical plane for ankle (a) and knee (b) markers.

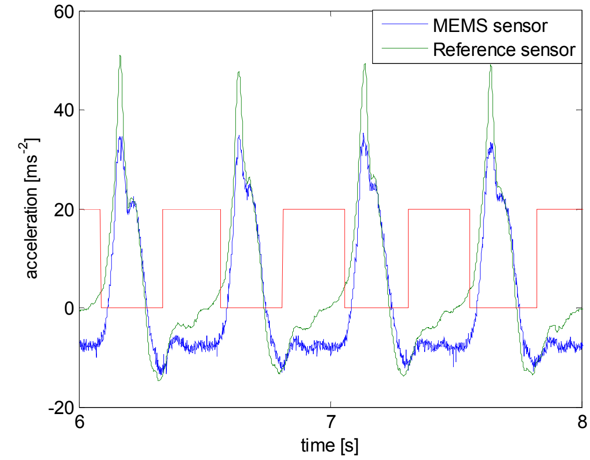


Fig. 5. Vertical acceleration measured by reference and MEMS accelerometers at the hip

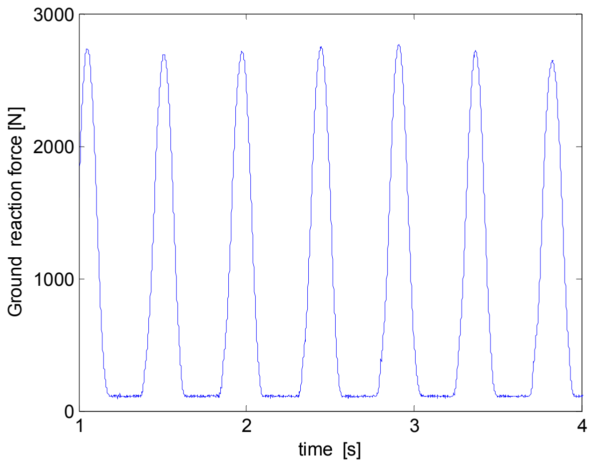


Fig. 6. Force measurement from the force platform.

Figure 7 presents such angles in the case of natural hopping. When the subject is properly trained and timed on the reference frequency, it is possible to obtain very repeatable values. A statistical analysis is possible by considering the maximum and minimum values together with the angle at landing and takeoff obtained with the help of the contact signal.

The knee and ankle angles provide important information to develop a multi-segmental model of the leg. In future we are planning to carry out such a measurement in two independent ways: besides the indirect measurement from the marker positions as shown, a direct measurement by an Analog Device MEMS gyroscope (ADXRS 610), positioned on the leg segment. Of course this redundancy will provide a validation of the angle measurement obtained from video processing.

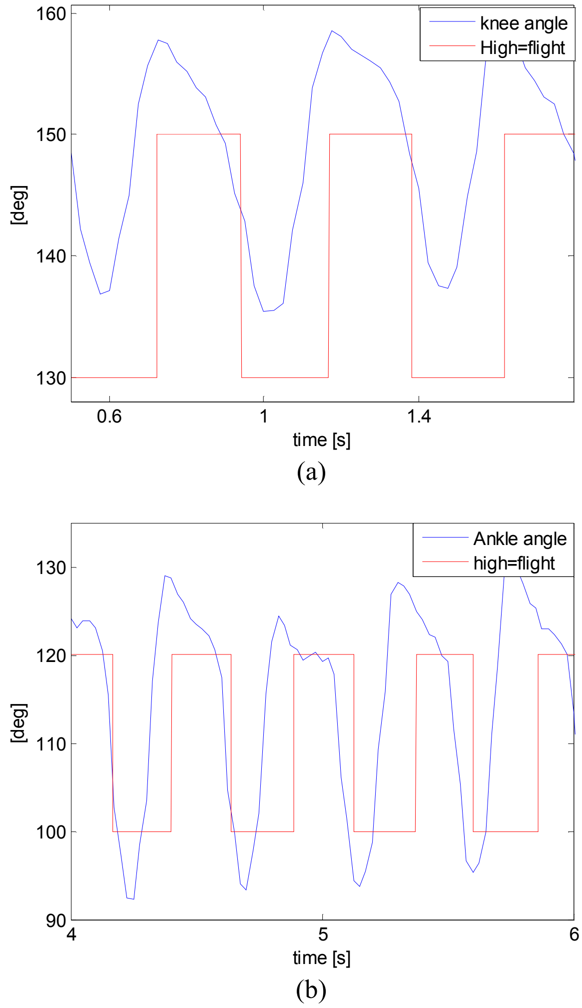


Fig. 7. Angles at the knee (a) and ankle (b) .

4.1. Reliability and uncertainty of the measurements

As already depicted the reliability of the measurement data is guaranteed providing a detailed metrological characterisation of the single measurement chains and a validation in the field enabled by sensor redundancy. The former approach has been already described, table 2 gives some figures to evaluate the measurement uncertainties. In particular the use of MEMS sensor with wide tolerances requires a detailed characterisation of each unit, which has been performed in the lab both statically and dynamically.

Table 2 Relative expanded uncertainties for the various measurement chains

Sensor		**Uncertainty**
Force Platform	Static	1%
	Dynamic[1]	10%[2]
MEMS	Static	7%
	Dynamic[1]	10%[2]
Video	Static[3]	3%

[1] Frequency response module.
[2] Expanded uncertainty p_0=0,95.
[3] Referred to a displacement of 200 mm.

When evaluating the overall uncertainty in the measurement the repeatability and reproducibility effects due to variations among different repetitions and different subjects dominate the uncertainty budget.

As regards the validation in the field, several possibilities are available and we have already described some of them previously:

- comparison of the MEMS and standard accelerometers at the hip;
- comparison of the displacement as evaluated from the double integration of the acceleration with the data available from the video system;
- comparison of the angles between the memes gyroscope and video system data;
- verification that the length of the various leg's segments do not vary during the gesture.

These controls provides the consistency of the experimental data and avoid possible errors due to malfunctioning of the sensors and/or wrong placement.

4. CONCLUSIONS

The paper presented an integrated measurement system devoted to the measurement of kinematics and dynamic quantities during simple gestures, with the aim of providing useful data for the development of biomechanical models.

The measuring systems includes a force platform, MEMS accelerometers to measure leg segments acceleration, and a 2D video system to localise the position of several markers along the leg and the body.

One of the main goals was the reliability of the measurement results, so first of all a detailed metrological characterisation of both the force platform and the MEMS accelerometers has been carried out, then the system provides a set of opportunities to validate the results during its use in the field.

Possible applications of the system regards gestures that can be well approximated in two dimensions, such as cycling, walking, stepping down. As a test case the system was used to characterise the hop in the place gesture and some experimental results were presented. We are planning to extend this measurement campaign to more subjects to have the possibility of some statistical analysis.

At the moment we are improving the exploitation of all the huge amount of available information, for example the integration of the acceleration signals and some statistical processing of the results.

In future we will add a gyroscope sensor to improve the reliability of angular measurements, and we will move to a high resolution and high speed video system to improve position measurements.

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