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Angular Moment and Corrective Forces in Human Walking Processes: Sensor and Actuator Analysis †

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Abstract: Taking into account the dynamics of a human body in its daily movement, one can study the forces that are generated in its variations with respect to a normal walk. These forces can be reduced, generating an opposite force through some device if one takes into account that their magnitude is not very large in some cases. This paper outlines results obtained from the sensorization of a human body in uniform movement, and changes in angular velocity and moment of a force produced by different inflections in normal movement. The aim was to calculate the moment of a force thanks to the measured angular velocity, and then study the opposition to this movement by using the produced reaction by the conservation of angular moment (gyroscopic effect). The study was carried out through the positioning of different sensors that were placed to analyze points of interest of the movement. In this study, we were able to appreciate changes in the variables to study up to two orders of magnitude at the generated moment, when the movement went from being uniform, which is equivalent to a walk, to the situation of an inflection, for example, a fall or bending over. With the collected data, the prediction of a fall could be studied and perhaps avoided.

Keywords: sensorization; angular velocity; fall; acceleration; moment of a force; gyroscope; inflection; bending over

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1. Introduction

Gyroscope effects are related to rotating bodies. In this work, stabilization reactions were analyzed and exploited using different sensors related to this effect [1–3]. These sensors were located at strategic points of a human body in order to study the angular velocities and global accelerations of the movement of said body in different situations, from a walk to various inflection types. By obtaining these parameters, the generated moment by the body can be studied; thus, we can analyze possible ways to anticipate a fall, or differentiate between it and bending over [4] through some kind of automation to control, like in some robots or even in satellites [5,6]. Having the data of falls, we can take advantage of the gyroscopic effect to cushion/avoid it, like other studies carried out to improve the position/effort of a person [7,8]. This type of sensorization has been carried out on specific types of persons or through other types of sensors because such studies were focused on a specific problem [9]. In this paper, we studied a subject but, in order to extrapolate to anyone, we studied the dynamics [10,11]. In this case, it was about being able to extrapolate the obtained results to any person, since the moment of a force that a gyroscope generates is proportional to the generated force in an inflection. The measures that were made in terms of accelerometry were not directly used in the study of the generated moment by the body, but rather served us to see its kinematics. The state of the art surrounding the study was analyzed to see near or similar cases. We observed, as previously mentioned, other techniques and purposes of this type of study. Then, the measurements (sensorized) of areas of interest that were considered to take into account the whole body (to treat it as homogeneously as possible) were made for different situations. We also calculated the moments and different cases of interest. Regarding the state of the art related to this study, there have been sensorizations related to angular momentum in areas that provide interesting results. Limbs, for example, do not provide relevant information on what is being studied.

2. Results

2.1. Generated Moment

In this section, the results of the generated moment are explained. The main objective of this study is to calculate the moment of a generated force by a human, thanks to the measured angular velocity in an individual with the final purpose of detecting differences between a walk and different inflections, such as bending over or suffering a fall. With angular velocity and time, we can obtain angular acceleration. The moment can be defined as:

$$\vec{M} = I \cdot \vec{\alpha} \rightarrow M_x = \frac{1}{2} \cdot m \cdot l^2 \cdot \alpha_x; \qquad M_y = \frac{1}{2} \cdot m \cdot l^2 \cdot \alpha_y; \qquad M_z = \frac{1}{2} \cdot m \cdot l^2 \cdot \alpha_z, \tag{1}$$

where I is the moment of inertia that is proportional to mass (Kg) and length (m), and α is the angular-acceleration vector $[rad/s^2]$ [12]. To obtain the angular acceleration in the previous equation, measurements of angular velocity had to be performed, ω, and are represented in time intervals of 20 ms while extracting angular acceleration. Since M and α are vectors, they could be separated in their spatial components. The mass that appears in Equation (1) is that of the individual wearing the measuring device (the mass of the device was negligible), which was m = 80 Kg, and length is the height at which the devices were placed. For the following graph (Figure 1), corresponding to Measurement (3), height was $l_3 = 1.65$ m .

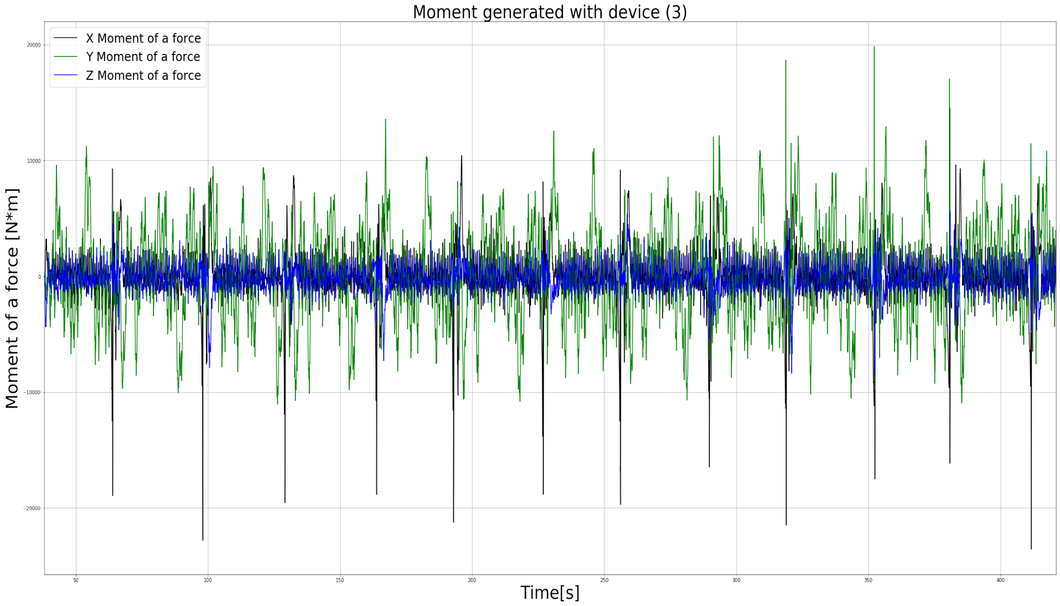


Figure 1. Generated moments for Measurement (3) in walk–fall change.

Figure 1 shows that there were not only inflections in one direction, but the motion in the x-axis is the one that interested us the most, because it was taken as the reference direction in the turning inflections. Figure 2 shows the variations reached for the maximum angular velocity for three of the mentioned situations. In green are the stumbles that were slightly random in terms of magnitude period, amplitude, and angular-velocity variation. In the case of bending over, in blue, the movement of going to the ground and returning to the initial position is clearly seen in the wave, so bending over was easier to automate. Note that, although all measurements were made for a single subject, the obtained results, at a qualitative level, can be extrapolated to the movement of any person, since differences are proportional to these results.

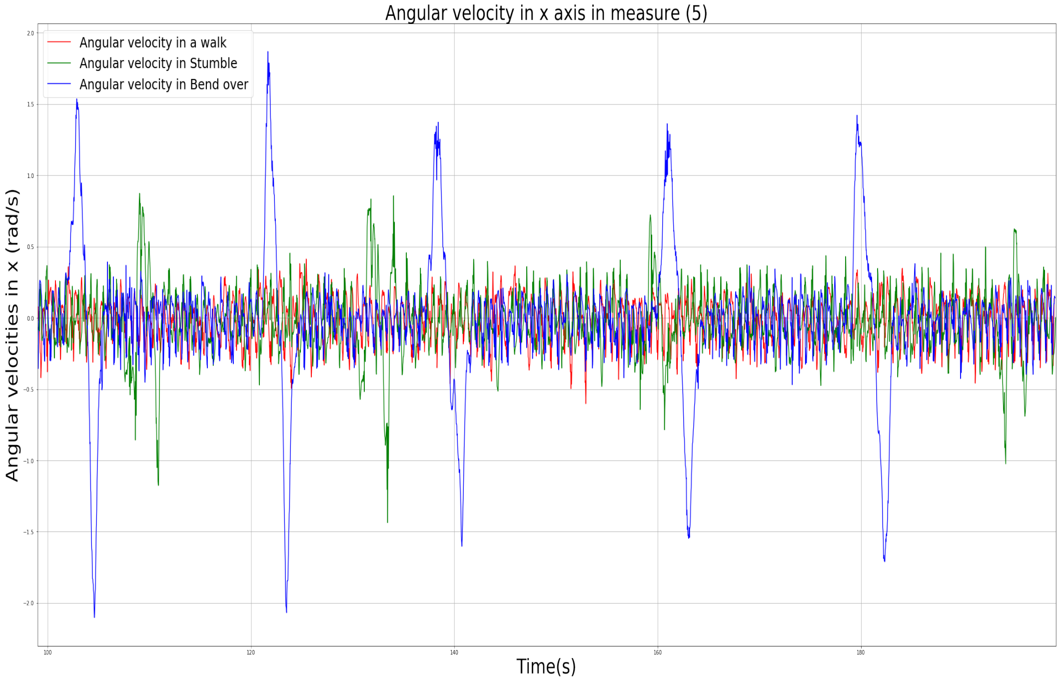


Figure 2. Differences between walking, stumbling, and bending over.

Table 1 shows the most relevant results for Measurement (3). It reflects the maximum moment reached (in absolute value that corresponds to a negative peak in the graph), which gives us a higher level to begin to investigate how to avoid or soften it. It also give an average moment of walking with which one can see the minimum values from which the device would act.

Table 1. Interesting force moments in the study: three directions correspond to maximum reached in a fall (with its value in module), and the last is a confidence interval in a walk.

Data	Maximum x Directon	Maximum y Directon	Maximum z Directon	Walk Interval
Moment (N*m)	23,551.88	19,846.18	8602.02	$\sim \in(-218.67, 218.67)$

Table 2 shows the angular-velocity values for different situations (Figure 2) along with the periods, showing differences in both amplitude and period for different cases, which allows us to work and calibrate device performance.

Table 2. Summary of Figure 2 (module values).

Data	Walk	Stumble	Bend over
Maximum angular velocity (rad/s)	0.602	1.447	2.103
Period (s)	1	∼2.5	∼5

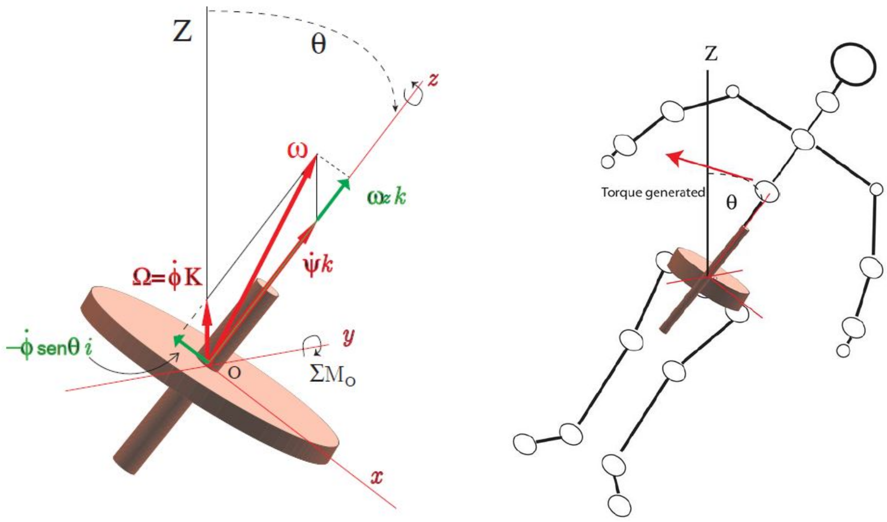
2.2. Applied Moment Study

Once the real case was studied and we obtained experimental data on a real individual, a computer simulation is discussed in this section that focused more on the gyroscopic study. The case of a gyroscope that is composed of a disc rotating around its axis is also interesting. The rotation axis is the resulting angular moment direction of the disc mass rotating movement. The structure that held the disc-axis supports was mounted on a horizontal axis that could also rotate. This second axis allowed the angular moment of the rotating disc to adopt any direction in the vertical plane that was perpendicular to this axis. Assembly was completed with a horizontal platform that held the gimbals in a way in which they could freely rotate around the vertical axis. The addition of this third axis allowed the angular moment to adopt any orientation. In theoretical terms, the gyroscope is an isolated system and the gimbals materialize the isolation, with the external system represented by the platform. The case study we propose in this subsection is the orientation control of a gyroscope using a horizontal external force that causes vertical rotation in the gimbals. The axes could be reoriented according to the system that we take. Its effect is the apparition of a dynamic moment that changes the angular moment. The gyroscope is then reoriented perpendicularly to the force.

The manifested moments of force in the conservation of angular momentum of the gyroscope are extensible to different scenarios for stabilizing a body or device by inducing inertial gyroscopic reactions. To this end, the behavior of the gyroscope was simulated (Figure 3a). Different situations were considered, and we analyzed the influence and exchange rate between the main variables of the model. We took into account that the resulting moment into the axis was:

$$\sum M_O = \Omega \times L_O \tag{2}$$

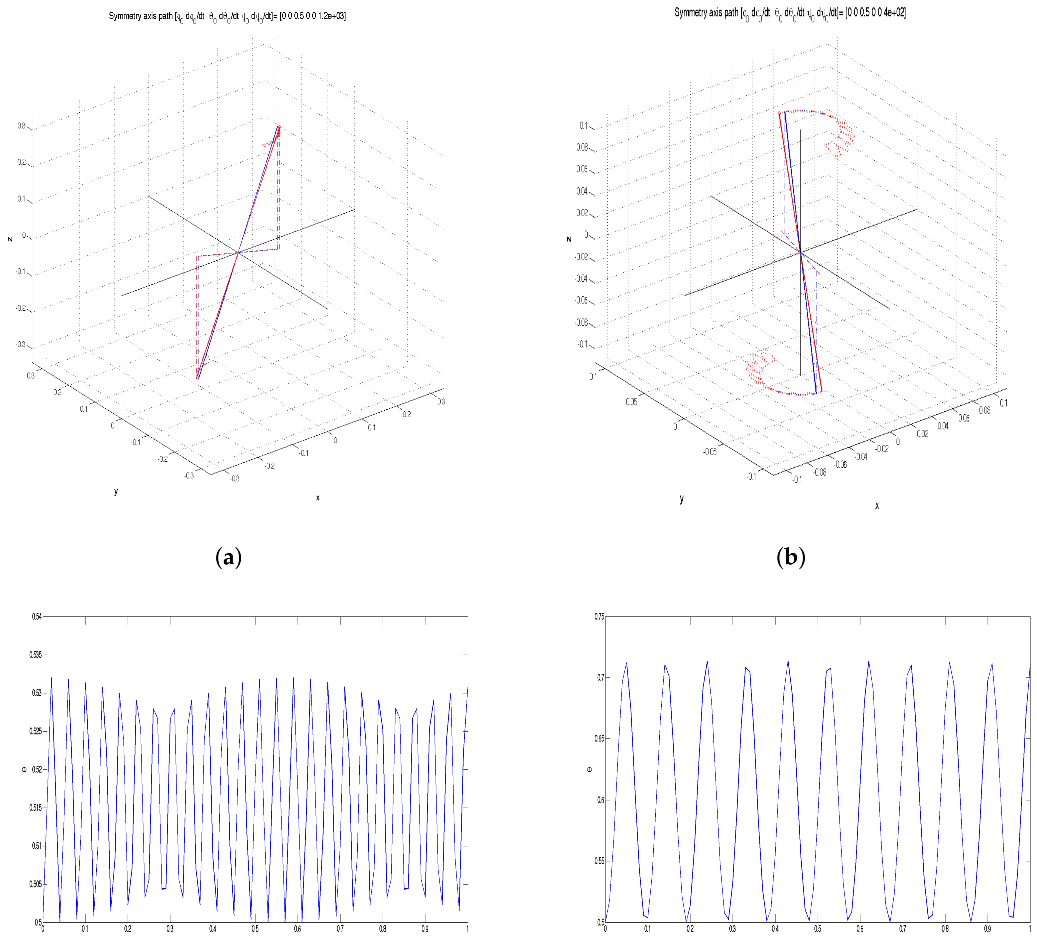
L_O being the angular moment of the body relative to fixed reference system $OXYZ$, and Ω the angular velocity of the reference system rotating with respect to $Oxyz$. The Euler equations modeled their behavior and allowed simulation.



(**a**) (**b**)

Figure 3. Gyroscope: (**a**) Central section, axis, Euler angles. (**b**) Torque produced in gyroscope and regulated angle (θ).

A simulation of the relationship between angles of rotation, precession, and nutation, and the pair of forces involved on the Z and y axis was performed. Figure 4 shows the result of the system simulation with the solved differential equations that modeled this behavior. This simulation analyzed the relationship between stability angle θ and rate of change of angular velocity $\dot{\phi}$, keeping a constant speed of rotation $\dot{\psi}$. The rate of change of the angular velocities in the perpendicular axes was at a stable angle θ producing moments of force (torque) that made this possible. A gyroscope consisting of a disk of 1 Kg, r = 12 cm, to 12,000 rpm, placed at the centre of gravity of a person of 60 kg, could counteract the process of falling when an angle of $\theta = 5^o$ is reached.



(**a**) (**b**)

(**c**) (**d**)

Figure 4. Gyroscopic movements: (**a**) 1200 rad/s rotating mass; (**b**) 400 rad/s rotating mass. (**c**) Regulated set point θ = 0.5 rad and 1250 rad/s; (**d**) regulated set point θ = 0.5 rad and 400 rad/s.

3. Discussion

As expected, differences were obtained for angular velocity and momentum of a force generated for different situations. In the case of the moment, as mentioned before, changes became two orders of magnitude in the inflections of the fallen type with respect to the normal walk of the person. In the case of the angular speeds of most everyday situations such as walking, stumbling, and bending over, differences were less noticeable, but sufficient in signal period and amplitude (angular velocity) to be able to adjust the device to be developed.

Since Measurement (3) was one of the highest momentums of a force can reach, it was selected as a sample of the results in this article. The corresponding devices to other parts of the body gave proportional results to that of represented Device (3), but could not be more detailed due to the size of the article. When changing the height, the moment of inertia changes and, depending on oscillation of that part of the body, angular velocity changes. Accelerometers do not give sufficiently relevant information since limb movement is more random.

4. Matherials and Methods

Sensorization was produced by means of 9 devices that incorporate accelerometers and gyroscopes. The positions of these devices and measurement locations were: (1) left leg at midpoint between knee and pelvis, (2) right leg at midpoint between knee and pelvis, (3) between shoulder blades, (4) fourth lumbar, (5) in the nape, (6) left arm at tricep height, (7) on the chest, (8) right arm at tricep height, and (9) on the abdomen (see Figure 5). Measurement rate was every 20 ms or, in terms of frequency, 50 Hz. At first, measurements were made taking points every 200 ms, that is, the total number of points was 10 times smaller, so detecting the beginning of the inflections was more deficient. In total, there were 50 measurements (points) per second. Accelerometers were only used in the extremities, while gyroscopes were centered at the trunk. Legs and arms did not provide us with relevant data about angular velocity, so that we took into account the orientation when someone bends over to detect differences between flection or fall. This sensorization was performed on a young individual (24 years old).

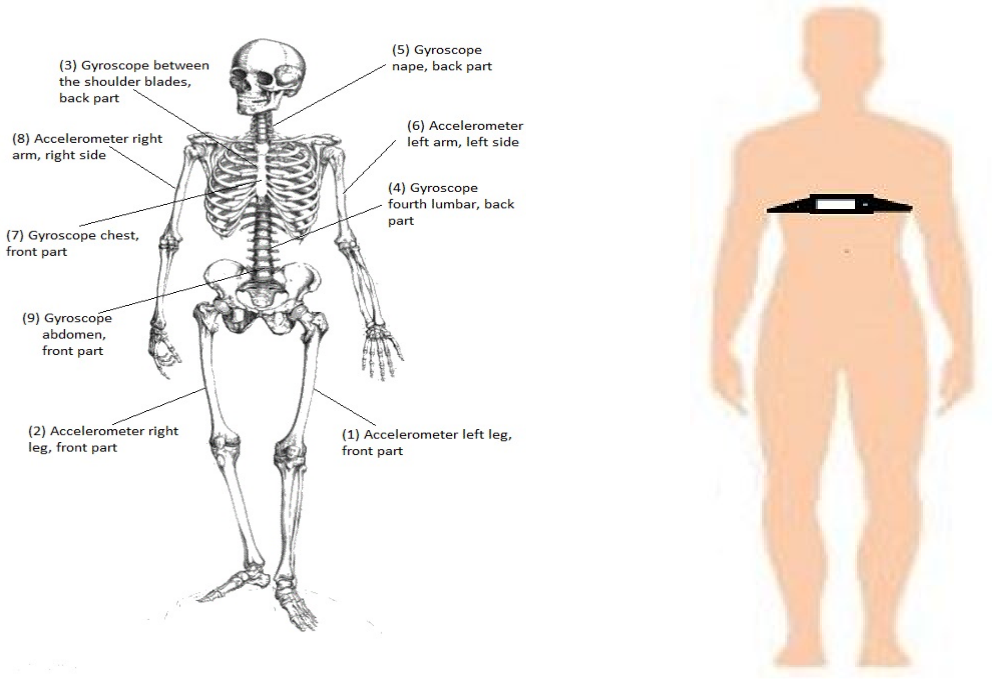


Figure 5. Sensor distribution. (**left**) Device position and (**right**) device (7) placement.

It can be observed that the three axes were important since no inflection is perfect in one direction. The sensors (Figure 6) collected information that was measured by applications created for this purpose.

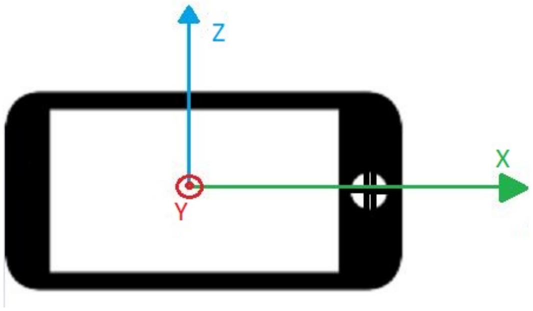


Figure 6. Sensor axis.

These data, in CSV form, were sent to the computer via mail and processed by it. Many graph values are negative due to device orientation. That is why, as was written in the results section, the work was focused on the absolute values of point-of-interest amounts. The corresponding sensors to the trunk and, therefore, to the angular velocities, offered us interesting results on the x and z axes. Once it had the measurements, it performed a "data clean" and graphed them to appreciate the inflections. From these inflections, among other data, the values of angular velocities were extracted and the corresponding moments calculated.

5. Conclusions

With all these collected data, we can start to study developing some type of object that helps to prevent such falls. If it can study generated moments in the dynamics of a human body in different situations, it can then see how to counteract them and stabilize the subject in question. We also concluded that relevant information is now only obtained from data provided by the trunk, and not by the extremities. Frail elderly people are likely to suffer falls. This paper contains the initial work to determine if gyroscopes can be used to exert forces that help to counteract loss of balance that triggers the onset of a fall. On detecting deviations of the angular momentum of a gyroscope carried by a person when the carrier loses their balance, we propose to apply a light force of control on the gimbal to force the angular moment to keep its orientation of reference. We evaluated that a gyroscope of 1000 g could be enough to help keep upright a person of 60 kg if it were rigid and that diverted 5^o from the vertical. Our conclusion is that this preliminary result justifies going on working to develop a wearable gyroscopic system, such as a belt or a vest.

Author Contributions: F.J.F.P. and J.M.G.C. performed formal analysis and conceptualization. The experiment phase was implemented by J.J.P.M. The state of the art, results, and conclusions were outlined by F.J.F.P. and J.J.P.M. Validation was realized by F.J.F.P., J.M.G.C., and J.J.P.M.

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