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# Comparison of intra-individual physiological sway complexity from force plate and inertial measurement unit

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## Abstract

Center of Pressure (COP) is a clinical measure to investigate the effect of sensory input disturbances on postural stability in healthy, old population as well in people suffering from neuromuscular disease. Increased center of pressure velocity and sway area are interpreted as decreased stability or poor balance and are associated with fall risk. Body mounted inertial sensors have shown great promise as an easily implemented clinical measure of balance. The aim of the present study is to investigate if force plate and accelerometer measurements provide similar physiological information when approximate entropy (ApEn) are evaluated from the time series. Seven Young and thirteen older individuals (two with fall history and nine without any past fall) participated in this study. There were different complexity measures in healthy young and old participants when both force plate and Inertial Measurement Unit (IMU) were assessed during the same time interval. Thus different control mechanisms are underlying to control trunk sway as measured by IMU than that of COP measured by force plate.

### Keywords

postural stability; Approximate Entropy; complexity

## INTRODUCTION

The control of balance is vital in performing all activities of daily life. As standing upright is inherently unstable, small deviations from an upright position may result in gravity-induced torques and leading further to corrective torque to counter the destabilizing torque due to gravity[1]. This continuous process involves contributions from sensory and motor systems and generates a pattern. Centre of pressure represents the resultant of gravitational forces and muscular stabilizing forces [2]. This ability to maintain the control of the projection of centre of mass within the stability limits during quiet standing has frequently been assessed by the use of force- plates. A high degree of association has been seen between COP and trunk sway (measured using an Inertial Measurement Unit-IMU)[3], thus qualifying IMU as a cheap clinical balance assessment tool[4].

Non-linear dynamics is a powerful tool to understand neuromuscular control mechanisms involved in biological time series such as COPx (Anterio-posterior axis) and COPy (Mediolateral axis). Approximate entropy (ApEn) is a recently developed statistic quantifying regularity and complexity that appears to have potential application to a wide variety of physiological time-series data. Approximate entropy (ApEn), is an approach to quantify the complexity and regularity of a system, which was introduced by Pincus [5]. It suggests that postural stability arises from the combination of specific feedback mechanisms and spontaneous properties of interconnected neurons, thus a weak or degraded neuromuscular mechanism may be characterized by an increased irregularity in the physiological time series[6, 7]. Here in this work ApEn is considered to provide a direct measurement of feedback among neuro-muscular connections, and low ApEn would indicate high predictability and regularity of time series data, where as high ApEn values would indicate unpredictability and random variation[6, 8].

The aim of this work is to assess whether COP sway measured by forceplate and IMU carry similar non linear dynamic information.

# METHODS

## Subjects

Seven healthy young adults and thirteen elderly (2 participants had more than 2 falls in previous year) participated in this study (Table 1). Basic body function data (height, weight, dominant foot) was collected and prior to the study, all participants gave informed consent and answered a questionnaire inquiring about their medical history.

## Data collection protocol

Data were collected for each participant in one 20 min session. Two inertial measurement units were used. One was affixed at sternum level of the participant and the other was tapped on forceplate as soon as data collection started. Each trial was collected for 75 seconds. The peak in data of Force plate and IMU were used to synchronize the time series. Time-series data was truncated and extracted for 60 seconds, after 2 seconds of synchronization peak. A triaxial accelerometer, centered roughly over the sternum, was secured to each subject using velcro straps that wrapped around the subject's torso. The distance between the accelerometer and the ground was measured.

## Apparatus

An AMTI force plate embedded into a flat level surface was used to record the COP of the subjects. In addition, An Inertial Measurement Unit (IMU) was used to quantify both static and dynamic postural tasks. The IMU consists of a MMA7261QT tri-axial accelerometer, an IDG-300 gyroscope (x and y plane) and an ADXRS300 gyroscope (z-plane uniaxial). The sway path of the accelerometer was calculated using equations from Mayagoitia et al [4].

**Approximate Entropy—**The algorithm for estimating ApEn was first reported by Pincus [5]. We here explain that approach as applied to Center of pressure (COP) data. ApEn is defined as the logarithmic likelihood that the patterns of the data that are close to each other will remain close for the next comparison within a longer pattern. Given a sequence of total **N** numbers of COP (x or y coordinate) like COPx(1), COPx (2),………, COPx (N), similarly for COPy(1), COPy (2),………, COPy (N). To compute ApEn of each COPx & COPy data set, m-dimensional vector sequences pm (i) were constructed from the COP time series like [pm (1), pm (2), ……………., pm (N-m+1)], where the index i can take values ranging from 1 to N-m+1. Where the distance between two vectors pm (i) and pm (j) is defined as |pm (j) - pm (i)|,

$$G_i^m(d)=\frac{1}{N-m+1}\text{such} \quad \text{that}|P_m(j)-P_m(i)|<d$$

Where **m** specifies the pattern length which is 2 in our study, **d** defines the similarity coefficient which has been set at 0.2% of the standard deviation of 7200 COP data (collected for 1 minute at 120Hz sampling frequency) which can produce reasonable statistical validity of ApEn [6]. These constants yielded statistically reliable and reproducible results. Cim(d) is considered as the mean of the fraction of patterns of length *m* that resemble the pattern of the same length that begins at index i. ApEn is computed as

$$ApEn(N, m, d)=(N-m+1)^{-1}\sum_{i=1}^{N-(m-1)} lnC_i^m(d)-(N-m)^{-1}\sum_{i=1}^{N-m} lnC_i^{m+1}(d)$$

In our study, we use data set of 7200 adjacent COP data points. We divide the data set into smaller sets of length, i.e., m = 2. This amounts to 3600 smaller sub sets. The next step is to determine the number of subsets that are within the criterion of similarity d = 0.2% of the standard deviation of 7200 COP points. Then we repeat the same process for the second subset till each subset is compared with the rest of the data set.

## RESULTS

As seen from Table 1, Eyes closed condition increases complexities from that of eyes open condition in all three groups i.e.. healthy young, healthy elderly and elderly fallers as shown by force plate time series data. Time series from IMU shows

## DISCUSSION

Our results showed trunk sway does not provide the same physiological time series information as provided by center of pressure. Stabilograms and IMU inclinometer trunk sway were used to provide anterio-posterior (COPx) and mediolateral (COPy) time-series. As seen from Figure 1 & Figure 2, IMU ApEn values in elderly individuals are underestimated where as for healthy young IMU ApEn values are over-estimated when compared to the ApEn values computed from time series of COP from force plate. Six young and six old participants data is compared as shown in Figure 3 for open eyes condition. Older people were found to have higher complexity (as seen by higher ApEn values) and younger were found to have lower complexity from the time series measured by force plate. On the contrary, when IMU time series were compared it showed higher complexity for younger than older in some participants. This suggests poor control mechanism of elderly to maintain postural stability as measured by COP at force plate. Where as elderly people have better developed control mechanisms than younger ones for trunk sway and to help in balance maintenance.

## CONCLUSIONS

To understand non-linear dynamic influence of postural stability from two different measuring devices force plate and IMU, an experiment was designed to collect data from healthy young, healthy oldera and elderly fallers. Postural stability data was collected from both measuring instruments simultaneously and with two conditions i.e.. eyes open and eyes closed. Approximate entropy (ApEn) complexity index was adopted to quantify the complex variability of COP signals in the subjects AP and ML directions. The experimental results reveal that forceplate COP signals measured from elderly more complex than healthy young subjects , where as on the contrary IMU COP signals measured from elderly were found to be less complex than healthy young individuals. This suggests the presence of different control mechanism at foot COP measured by forceplate and that of trunk sway measured by IMU at trunk. The ability to adjust physical balance in AP direction of elderly

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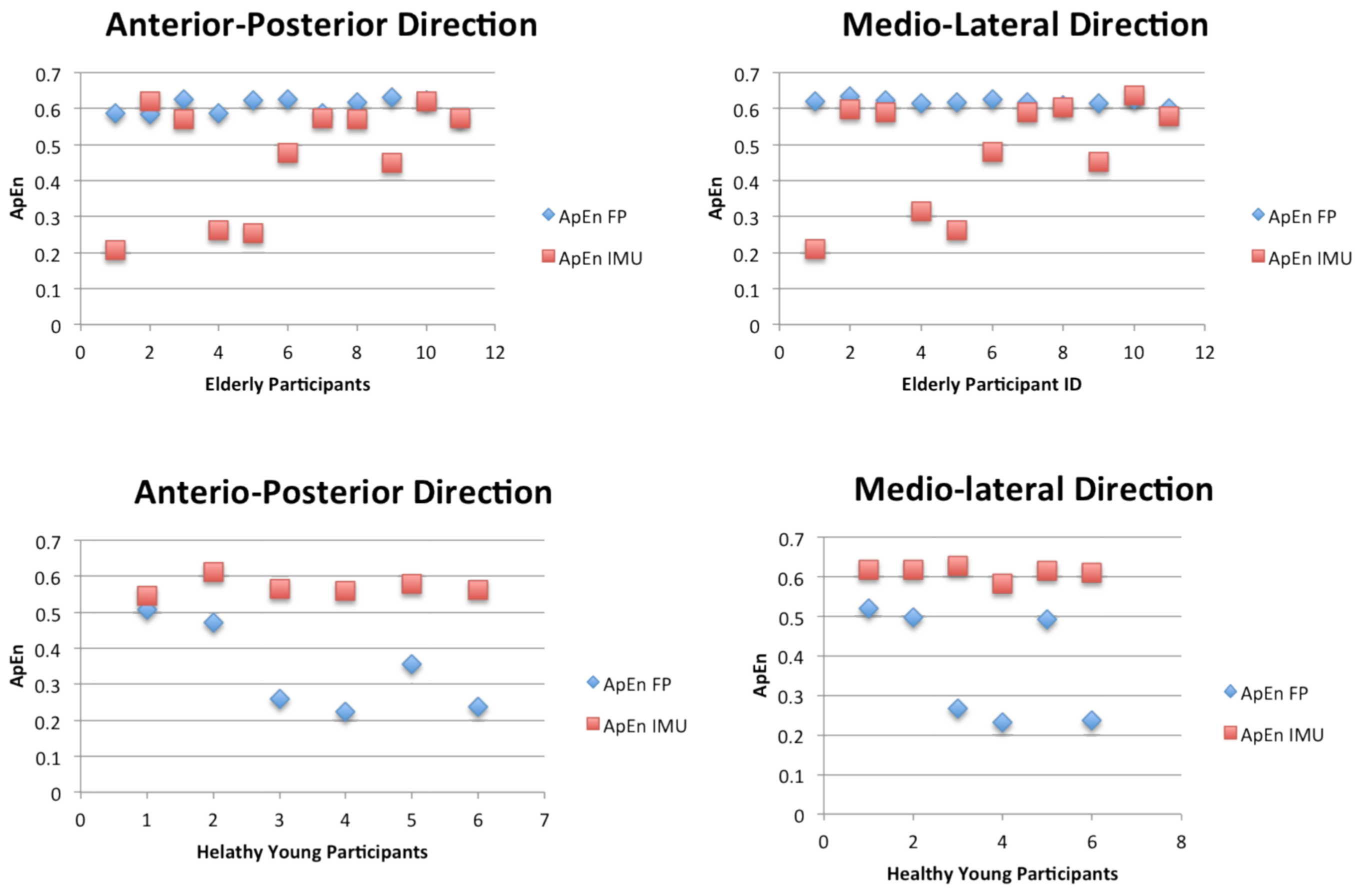


**Figure 1.**
ApEn Values from COP time series from Force plate and IMU when postural stability data was acquired in open eyes condition

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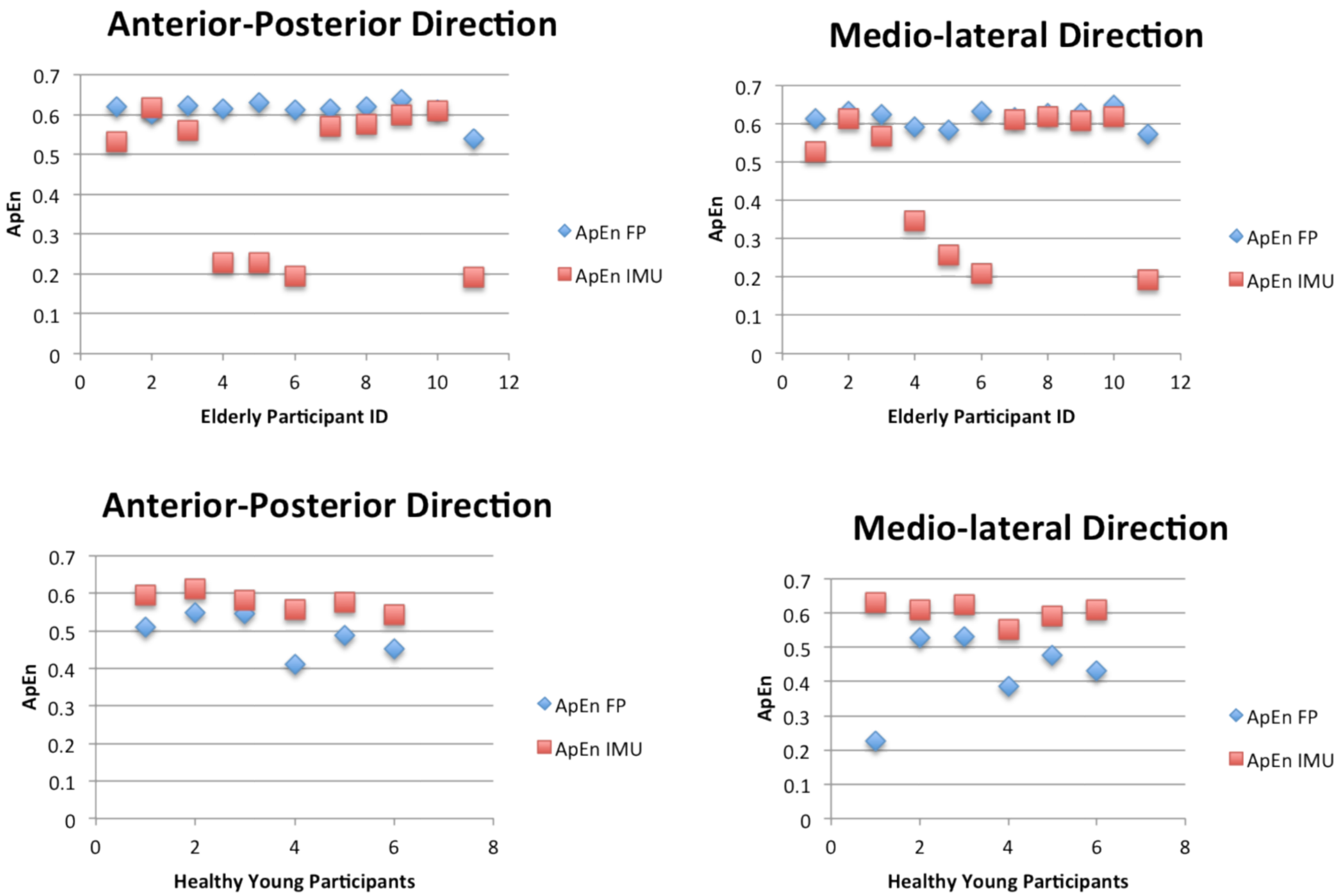


**Figure 2.**

ApEn Values from COP time series from Force plate and IMU when postural stability data was acquired in closed eyes condition.

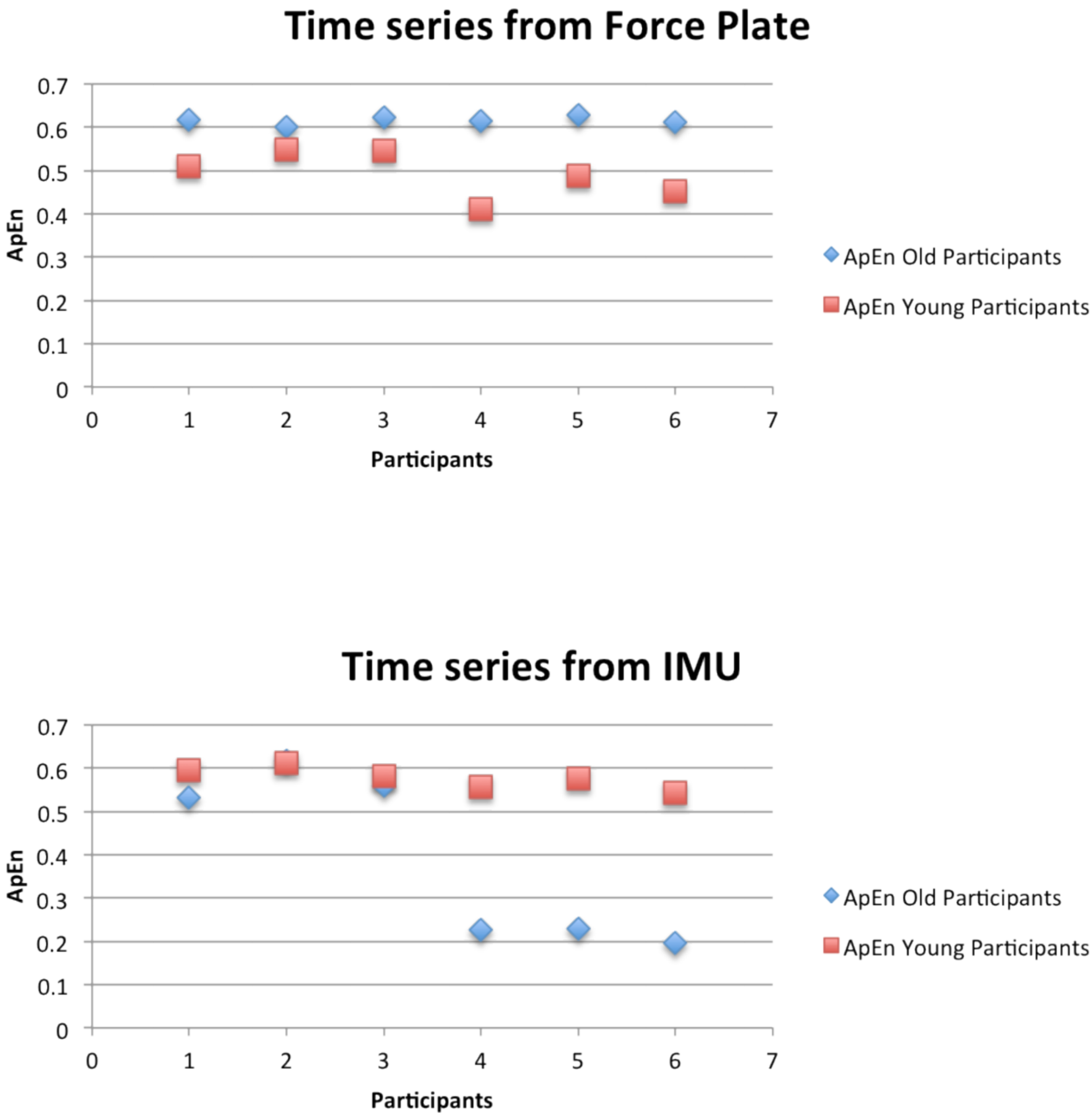


**Figure 3.**
Six young and six older participants ApEn data was computed and compared with respect to time series (a) from force plate (b) from IMU's

**Table I**

Participant anthropometric information shown in the table below

| Group | # of Participants | Age (years) | Height (cm) | Weight (Kg) |
|---|---|---|---|---|
| Healthy Young | 7 | 29±3 | 160±5 | 84±8 |
| Healthy Elderly | 11 | 78±4.94 | 160±7.29 | 74±22 |
| Elderly Faller | 2 | 78±7.07 | 166±5.65 | 81±1.41 |

## Table 2

ApEn values of 1 minute time series data from open eyes and closed eyes condition postural stability data

| | Healthy Young | | | | Healthy Elderly | | | | Elderly Fallers | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Eyes Open | | Eyes Closed | | Eyes Open | | Eves Closec | | Eyes Open | | Eyes Closed | |
| | AP | ML | AP | ML | AP | ML | AP | ML | AP | ML | AP | ML |
| **Force plate COP** | 0.34±0.12 | 0.37±0.14 | 0.49±0.05 | 0.43±0.11 | 0.60±0.02 | 0.61±0.00 | 0.61±0.02 | 0.61±0.02 | 0.60±0.03 | 0.57±0.03 | 0 63±0.01 | 0.61±0.00 |
| **IMU COP** | 0.57±0.02 | 0.61±0.01 | 0.57±0.02 | 0.60±0.02 | 0.47±0.15 | 0.48±0.15 | 0.44±0.18 | 0.47±0.17 | 0.58±0.02 | 0.60±0.00 | 0.35±0.34 | 0.60±0.01 |