Analysis of Human Stepping Dynamics Using a Wii Balance Board with a Webcam: A Comparison Study

Ismet Handžić
Department of Mechanical Engineering
University of South Florida
Tampa, Florida, USA
ihandzic@mail.usf.edu

Kyle B. Reed
Department of Mechanical Engineering
University of South Florida
Tampa, Florida, USA
KyleReed@usf.edu

ABSTRACT
This paper demonstrates the assembly and verification of an inexpensive and straightforward stepping dynamics assessment system capable of simultaneously recording human lower limb motions, vertical ground reaction forces (GRF), and two dimensional foot center of pressures (COP) during the gait stance phase. This proposed system uses a single webcam video camera for motion analysis in the sagittal (side) plane. A color detection image processing Python script enables the webcam to track distinctly colored marker tape placed on the ankle and knee joint while stepping on and over a Nintendo® Wii Balance Board (WBB). The WBB is used to measure vertical GRF and foot COP. Marker positions and COP are used to construct a foot rollover shape (ROS), the effective rocker shape that a lower limb system conforms to during a step. The accuracy of our WBB-webcam system is evaluated by the comparing marker motion, GRF, COP, and derived ROS measurements to a commercial force plate (FP) and eight-camera infrared motion capture (IRMC) system.

Keywords
Nintendo Wii Balance Board, webcam, human gait dynamics tracking, foot center of pressure, roll-over shape

1. INTRODUCTION
Human locomotion is a fundamental human function, thus historical footprints of the analysis of human gait can be traced throughout ancient and modern history [1]. The quantification of walking dynamics is essential to human functional biology sciences such as gait biomechanics, pathology, rehabilitation, or sports sciences. Consequently, persons or laboratories involved in the assessment, optimization, research, or rehabilitation of gait must have the equipment that makes quantification possible. Although a complete gait analysis system includes equipment to measure body motions, ground stepping forces and pressures, electromyography (EMG), and oxygen consumption, three of the most commonly analyzed parameters are body motions, stepping forces, and foot center of pressures [2, 3]. There is a vast selection of distinctly different commercial systems to accommodate the assessment of these gait parameters [2, 3], however many of these systems include equipment, software, and licenses that can be extremely costly. Depending on the nature of the analysis and application, gait analysis systems do not have to be magnificently fast or precise. For example, a gait analyst may use a less expensive video camera to record a person s stride length and walking speed in the side view. If millimeter-accuracy is not required, this task would not call for overly sophisticated infrared camera marker tracking technology. Further, inexpensive gait assessment equipment is highly desirable for home-based movement assessments [4, 5, 6].

For this reason there has always been a push for the development and applications of alternative, more widely available, and more economical technologies that are sufficient for certain types of gait assessment problems. One such technology is the *webcam*, a low-cost (<$30 US) and widely available type of video camera that generally interfaces with a personal computer. Webcams with a color and movement distinction algorithm can be used to track human body motions [7], or with the combination of retro-reflective markers, be used to effectively track planar leg motions when walking on a treadmill [8]. Plane view webcam analysis has also been used to assess the walking patterns of stroke patients on a treadmill [9].

A relatively inexpensive alternative to force plates (FP) and the measurement of vertical ground reaction forces (GRF) and foot center of pressures (COP) has been found in the *Nintendo® Wii Balance Board (WBB)* (∼$50 US). The WBB is a plastic board that is primary targeted towards the gaming industry and is instrumented with four force sensors, one at each corner. The individual reading of each corner sensor allows for the approximation of the COP [10]. Since its release in 2007, the WBB has raised interest in a broad spectrum of balance related research, some of which include Parkinson s disease gait freezing analysis [11], balance training [12], and more [10]. With a thirty-subject study, Clark et al. [13] found no difference between a WBB and a commercial FP for the assessment of standing balance COP. One study synchronized a WBB with a webcam in order to assess a home-based sit-to-stand balance rehabilitation system [14]. Although there have been numerous studies that use or validate a WBB for balance related applications, the authors

PETRA 2015 July 1-3 Curfu, Greece

DOI: http://dx.doi.org/10.1145/2769493.2769590

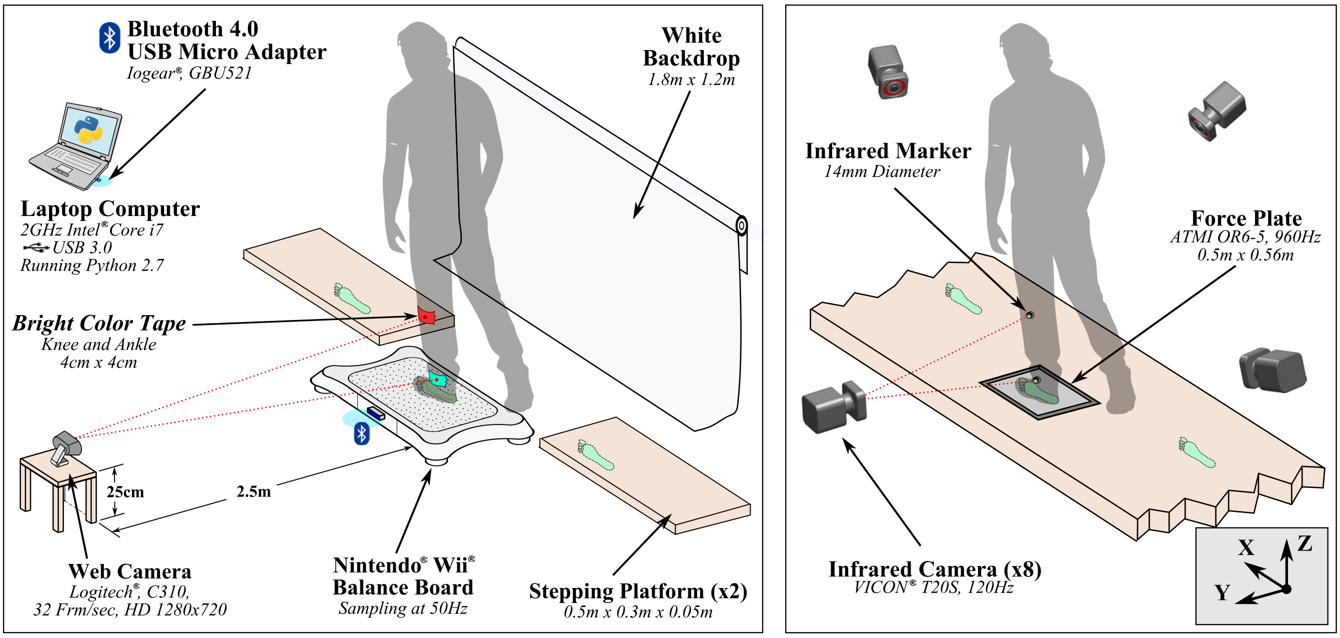

Figure 1: *(Left)* As the participant walks over a Nintendo® Wii Balance Board (WBB), the WBB records the subject s foot center of pressure (COP) and vertical ground reaction force (GRF). Two stepping platforms matching the WBB height are placed before and after the WBB for a consistent walking height. A webcam detects the position of the ankle and knee of the subject in the sagittal (side) plane by identifying two distinctly bright colored marker tapes during every recorded frame. *(Right)* The subject steps onto and over a force plate (FP), while an infrared camera marker tracking (ICMT) system records the position of the knee and ankle infrared markers in space.

were not able to find any studies relating the WBB and dynamic walking analysis. Furthermore, no studies were found that were able to simultaneously assess walking motions and ground reaction forces using a WBB and a webcam.

To help fill this gap, we present and evaluate a gait stepping dynamics analysis system consisting of the WBB for vertical GRF and COP measurements and a digital webcam for simultaneous ankle and knee position measurement. Because we are able to synchronize COP and marker position data, we are able to construct an effective foot roll-over shape (ROS) as an individual steps over the WBB. A foot ROS is the effective rocker shape that a leg-foot system conforms to and rolls over during a step [15] and is derived by using foot COP, ankle position, and knee position during the walking stance phase. The ROS concept can be implemented in the design and optimization of lower limb prosthetics [16] or foot wear [17].

2. EXPERIMENTAL SETUP

In order to evaluate the validity of our proposed system, we recorded the same stepping dynamics with our WBB-webcam system and a commercial force plate (FP) with infrared motion capture (IRMC) system.

2.1 Data Acquisition

One healthy participant (male, age 29, 93kg, 1.85m) was recorded walking over each of the two systems ten times. The number of trials was chosen because it was found to be a reliable number of trials required to establish a stable mean for ground reaction forces [18]. The participant wore the same athletic shoes (size 11US/45EU) while walking over both systems. To ensure steady state gait conditions, the participant started walking three strides before the WBB or FP and stopped walking three strides past the devices. The experimental setup of both systems can be seen in Figure 1.

For both system setups, GRFs, COPs, and marker position data was recorded during the left stance phase and only while the foot was in contact with the WBB or FP. The acquired data was not filtered in any way. Each trial data was temporally and spatially aligned to first ground contact, after which the mean and standard deviation of all ten trials was found. That is, each data point was averaged with the same data point in time of all ten trials. The ROS was derived in a manor outlined in [15]. All data manipulation and presentation was done using Python 2.7 including the 'matplotlib' library.

2.2 Wii Balance Board and Webcam System

2.2.1 Wii Balance Board

The participant walked in a straight line and over the WBB (51cm x 32cm x 5.3cm). Two wooden and solid stepping platforms were placed before and after the WBB to assure consistent walking height. Due to the WBB design, no horizontal GRFs were recorded and only vertical GRFs were acquired. Front-back (COPx) and side-to-side (COPy) COP positions on the WBB were approximated by using the two Equations outlined in [10]. The WBB was interfaced to a laptop computer via a bluetooth adapter (Iogear®) and the 'cwiid' and 'blueZ' Python libraries. The WBB sampling rate was 50Hz.

2.2.2 Webcam

A webcam (Logitech®, C310, HD 1280p, 32fps) was placed on a 25cm stool and a perpendicular distance of 2.5m from

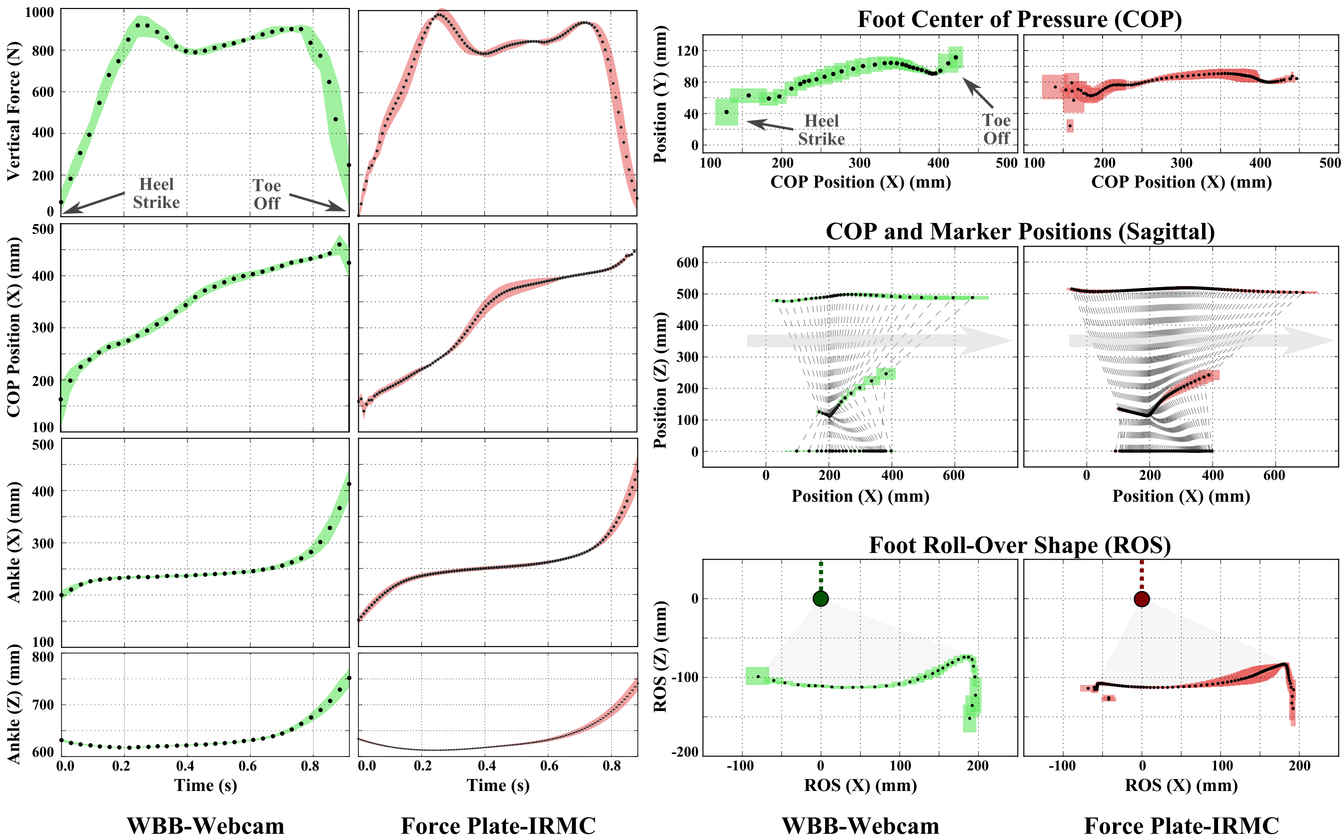

Figure 2: Stepping vertical ground reaction forces (GRF), center of pressures (COP), knee and ankle marker positions, and derived foot roll-over shape (ROS) for the WBB-webcam system compared to a force plate and infrared camera marker motion tracking. Note that black dots represent the intra trial mean, while the shaded region represents one standard deviation

the WBB, aligned to the WBB center (Figure 1 (Left)), and interfaced to a computer via USB 3.0 and the 'openCV' Python library. Two pieces (4cm x 4cm) of distinctly bright colored marker tape were placed on the participant's left ankle (lateral malleolus - blue) and knee (lateral epicondyle - red) joints, which were tracked by the webcam. In order to reduce the probability of the webcam falsely identifying surrounding colors, a plain white cloth backdrop was placed behind the entire webcam viewing scene.

2.2.3 Computer Algorithm Outline

To increase recording speed, the algorithm first simultaneously recorded all WBB and webcam data, subsequently processing it after each trial. To find the marker positions, the computer algorithm scanned each webcam captured frame, and in turn each frame pixel, for a specified red-green-blue (RGB) color range value specified to each marker color. For a set of identified pixels in each frame, the average horizontal and vertical pixel position was determined. This mean pixel position represented the position of the colored marker on the participant for that frame. In order to convert from on-frame pixel positions to actual millimeter positions, two points of known millimeter distance between them were selected by the algorithm for the first webcam captured frame. These selected points were in the participant's walking plane. By dividing millimeter distance with on-frame pixel distance, a conversion factor was found.

Although the WBB is able to sample vertical GRF and COP data at 50Hz, the complete WBB-webcam system was synchronized and read measurements at the webcam's sampling frequency of 32Hz, roughly four times slower than the FP-IRMC system.

2.3 Force Plate (FP) with Infrared Motion Capture (IRMC) System

For this system, the participant walked in a straight line and over a ATMI® OR6-5 biomechanics/force platform (51cm x 56cm), which was embedded in a 7m long wooden walkway as shown in Figure 1 (Right). Eight VICON® T20S infrared motion tracking cameras recorded the spatial position of two passive retro-reflective markers (⌀14mm) that were placed on the participant's left ankle and knee joints. The force plate recorded GRFs and COPs at 960Hz, however was sampled down to match the motion tracking system recording rate of 120Hz. The data acquisition was managed by VICON® Nexus® software.

3. RESULTS AND DISCUSSION

All data collected and processed can be seen in Figure 2. The general trend and magnitudes of the vertical GRF of our WBB-webcam were comparable to that of the FP-IRMC setup, however there are differences. Average peak heel strike force (0s-0.4s) was recorded higher with FP-IRMC. Also, due its lower sampling rate, slight GRF fluctuations at mid stance (0.4s-0.6s) were not recognized by the WBB-webcam setup. The average standard deviation for the WBB-webcam and FP-IRMC setup was ±70N and ±40N, respectively.

While the range of the COPx was comparable between the two setups, the WBB COP trend differs slightly during the first half of the stance phase where WBB COP was lower than the FP-IRMC setup. This may be due to the higher variability during the first half of the stance phase where COPx advances at a larger rate, nevertheless can again be deduced to the lower sampling rate. Most deviations of the COP occur as the participant s heel touches down and as their toe raises up.

The ankle marker position in both the front-back (X) and up-down (Z) direction is found to be in high correspondence. While the ankle marker moves at a maximum velocity of 1.9m/s, both setups record similar marker position trends, magnitudes, and deviations. Note that standard deviation increases linearly with increasing marker velocity at foot toe off. Both systems are able to identify the slight knee fluctuation in the up-down direction during the middle of the stance phase.

Despite the lower sampling rate of the WBB-webcam setup, it was able to use COP and marker position measurements to derive similar ROSs. Note that a greater variation of in ROS measurements were found during initial heel strike and terminal toe off, which is expected given the higher deviation values of heel strike and toe off measurements of COP and marker position. However, the majority of mid stance ROS was consistent in that it showed little variation between measured trials.

4. CONCLUSIONS

By assembling a human stepping dynamics assessment system using a widely available Nintendo® Wii Balance Board with a conventional webcam, we showed that it is possible to acquire good vertical GRF, COP, ankle and knee joint positions, and ROS measurements comparable to a commercial force platform and an infrared camera motion tracking system. Although our proposed system is applicable and viable for many gait analysis applications that require the interpretation of these gait parameters, it is no substitute for highly precise analysis systems with sharp resolutions and high sampling rates. Depending on the nature of the gait assessment or gait analysis environment (i.e, home-based), it may be unnecessary, complex, expensive, or unavailable to utilize such high-end analysis tools, thus our system provides a good alternative that offers acceptable results.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge Dimitrios Menychtas for his assistance in the collection of the force plate and infrared camera motion tracking system data.

6. REFERENCES

[1] A. Thurston, Giovanni borelli and the study of human movement: An historical review, *Australian and New Zealand journal of surgery*, vol. 69, no. 4, pp. 276 288, 1999.

[2] M. Whittle, *Gait Analysis*. Elsevier Health Sciences, 5 ed., 2012.

[3] G. Lee and F. E. Pollo, Technology overview: The gait analysis laboratory., *Journal of Clinical Engineering*, vol. 26, no. 2, pp. 129 135, 2001.

[4] F. Wang, *Motion analysis for in-home gait and balance assessment using inexpensive video sensors*. PhD thesis, University of Missouri Columbia, 2011.

[5] H. Zhou and H. Hu, Human motion tracking for rehabilitation: A survey, *Biomedical Signal Processing and Control*, vol. 3, no. 1, pp. 1 18, 2008.

[6] T. Russell, G. Jull, and R. Wootton, Can the internet be used as a medium to evaluate knee angle?, *Manual therapy*, vol. 8, no. 4, pp. 242 246, 2003.

[7] S.-F. Wong and K. Wong, Reliable and fast human body tracking under information deficiency, in *Proceedings of the IEEE Intelligent Automation Conference*, pp. 491 498, IEEE., 2003.

[8] C. Krishnan, E. P. Washabaugh, and Y. Seetharaman, A low cost real-time motion tracking approach using webcam technology, *Journal of biomechanics*, 2014.

[9] S. S. Kuys, S. G. Brauer, L. Ada, and T. G. Russell, Immediate effect of treadmill walking practice versus overground walking practice on overground walking pattern in ambulatory stroke patients: an experimental study, *Clinical Rehabilitation*, vol. 22, no. 10-11, pp. 931 939, 2008.

[10] D. J. Goble, B. L. Cone, and B. W. Fling, Using the wii fit as a tool for balance assessment and neurorehabilitation: the first half decade of wii-search , *J Neuroeng Rehabil*, vol. 11, p. 12, 2014.

[11] C. Fearon, E. Roudala, H. Nolan, and J. Gallego, Gait analysis and wii balance board use in freezing of gait in parkinson s disease, in *MDS 17th International Congress of Parkinson's Disease and Movement Disorders*, vol. 28, June 2013.

[12] S. H. Kim and K. B. Reed, Robot-assisted balance training for gait modification, in *Proc. IEEE Int. Conf. Rehabilitation Robotics*, 2013.

[13] R. A. Clark, A. L. Bryant, Y. Pua, P. McCrory, K. Bennell, and M. Hunt, Validity and reliability of the nintendo wii balance board for assessment of standing balance, *Gait & posture*, vol. 31, no. 3, pp. 307 310, 2010.

[14] C. Faria, J. Silva, and A. Campilho, Rehab@home: a tool for home-based motor function rehabilitation, *Disability and Rehabilitation: Assistive Technology*, no. 0, pp. 1 8, 2013.

[15] A. H. Hansen, D. S. Childress, and E. H. Knox, Roll-over shapes of human locomotor systems: effects of walking speed, *Clinical Biomechanics*, vol. 19, no. 4, pp. 407 414, 2004.

[16] C. Curtze, A. L. Hof, H. G. van Keeken, J. P. Halbertsma, K. Postema, and B. Otten, Comparative roll-over analysis of prosthetic feet, *Journal of Biomechanics*, vol. 42, no. 11, pp. 1746 1753, 2009.

[17] A. H. Hansen and D. S. Childress, Effects of shoe heel height on biologic rollover characteristics during walking, *Journal of rehabilitation research and development*, vol. 41, no. 4, pp. 547 554, 2004.

[18] J. Hamill and S. L. McNiven, Reliability of selected ground reaction force parameters during walking, *Human Movement Science*, vol. 9, no. 2, pp. 117 131, 1990.