ANALYZING THE CENTER OF MASS OF ATHLETES PERFORMING BOTH AN OPEN AND CLOSED SKILL EXERCISE

Amanda Delaney, Kimberly Bigelow
University of Dayton
Department of Mechanical Engineering
300 College Park
Dayton, OH 45469-0238
Telephone: 937-229-5374
Amanda Delaney delaneya2@udayton.edu

Mark Derriso
Wright Patterson Air Force Base
1253 Chestnut Street
Wright-Patterson AFB, OH 45433

Christine Kabban-Schubert
Air Force Institute of Technology
2950 Hobson Way
Wright-Patterson AFB, OH 45433

Ed Downs
ProTERF
6808 SW 81 Street
Miami, FL 33143

Abstract: In looking into the components of human monitoring systems, there are three main elements that comprise a system: sensors; data acquisition and communication; and data processing and analytics. Sensors that function with the purpose of sensing body movements or collecting specific physiological or biological parameters of an individual are typically known as wearables. Wearables used for capturing body movements are primarily inertial measurement units (IMUs) which utilize sensor fusion to combine the technology of an accelerometer, gyroscope, and magnetometer. Data obtained from these wearables may provide important insight into subtle differences in body movements that influence performance outcomes. The long-term goal of our work is to develop approaches that enable the prediction of an individual's performance in an open-skilled environment. The specific aim of this research was to determine how data from a full body IMU-based system could be used in detecting subtle movement differences in the execution of a pre-planned agility test versus a reactive agility test.
Ten healthy young adult males who were regularly physically active and had played on a

sports team within the past four years participated in this study. An Xsens Awinda 17 sensor suit was used to capture body movement data during the two agility tests. In both the pre-planned and reactive agility test, study participants stood facing six programmable illuminating lights, arranged in a 3 meter arc, 1.5 meters apart from each other, with the center being the starting position. For the pre-planned test the participant was informed which three lights, in order, that they would run to, with the requirement that they return to the center before advancing to the next light. For the reactive agility test, the participant was informed that all 6 lights would turn on, but the light they must run to and turn off would not have a color pair (ex. 3 red, 2 blue, 1 green). Participants were also asked to remember the color sequence of the three lights they turned off for an additional stressor.

Throughout the tests, each participant's center of mass (CoM) was tracked and compared to the direct path to the light with deviations calculated using standard sums of squares error (SSE). Study participants were broken into two groups for comparison: faster individuals and slower individuals based off of their completion time on the pre-planned agility test. Results from the pre-planned agility assessment indicated that the mean SSE for the CoM deviations to the light averaged 1.66 ± 1.43 meters for the faster performers and then 2.96 ± 2.05 meters for the slower performers. For the reactive agility tasks, the CoM deviations were higher with an average SSE of 5.82 ± 4.16 meters for the faster performers and 6.97 ± 7.60 meters for the slower performers. This suggests that the slower individuals were not just slow, but were likely slow because they were inefficient. Additionally, these findings indicate the notable increase in inefficiency generated by the uncertain scenario of the reactive agility test which corresponds to the 84% time increase from the pre-planned test.

Key Words: Human monitoring systems, Reactive Agility, Pre-planned Agility

Introduction: Over the years, training regimens continue to adapt to include new innovative training drills in order to enhance an athlete's skills. While revisions continue to shape the training realm, the essential goals remain the same: to assess athletes and improve their agility. With the evolution of training drills, the term agility has been modified from its previous meaning of solely the ability to move both quickly and effectively to now include an individual's ability to react to an uncertain stimulus [1]. To prevent confusion, the field has introduced the word reactive agility to coincide with the new definition. In adding the word reactive, the term more holistically describes the type of agility required in an open skilled sport. An open skilled sport is considered to be any sport in which the environment is unstable and requires the athlete to adapt to sudden changes (ex. football, basketball, soccer, etc.) [2]. A prime example of this is when a substitution is made and the defender has to change his or her approach to defending, or when a team is running a new play unknown to the opposing team, or simply during play where having a faster reaction and decision making time allows an athlete to beat their opponent. Reactive agility is more representative of what is seen during game play.

One of the drills innovated to incorporate this new inclusion of a response to a stimulus, which is essentially creating some sense of uncertainty, is known as the Reactive Agility

Test (RAT) [3,4,5]. The RAT has many different test setups. One of the setups includes a “Y” shaped path where two lights or lighted gates are placed at the ends of the fork and the player starts at the bottom of the “Y” [3]. Once a player runs to the fork a sensor trips one of the lights or gates to turn on and the player is to run to the illumination. The RAT setup has been used for both performing a pre-planned drill as well as the reactive agility drill. For the pre-planned test, the player is told which light/gate will be the one that illuminates before the drill starts, erasing the uncertainty of the drill. Another test variation includes a tester who initiates a movement to the left or right where the athlete is required to mimic the movements [4]. This version of the test is easy to run and includes the sense of an actual opponent. Timing equipment and cameras capture the athlete’s movements for further analysis. Instead of using a person as a tester, the test can also be virtual via a video screen and have the option of a pre-planned or reactive test as well [5]. Research comparing a pre-planned version to the reactive agility version has found that the reactive version yields slower reaction and completion times [3,4,5]. This increase in time lends itself to correspond to the fact that the athlete has to use his/her cognitive skills, such as decision making and reaction time, to overcome the uncertainty that was added. Cognitive flexibility, while not often assessed, is critical for making the correct adaptations to an environmental stimuli [6].

When looking to sense and measure the variables that allow a person to succeed, human monitoring systems become crucial. These monitoring systems are usually comprised of three main elements which include sensors, data acquisition and communication, and data processing and analytics [7]. For the purposes of monitoring human performance, wearable technology has emerged to sense anywhere from physiological data to biomechanical data. Wearables specific to biomechanical data, capture body movements through incorporating Inertial Measurement Units (IMUs) with algorithms to process signals and collect data. The IMUs work by combining the functions of an accelerometer, gyroscope, and magnetometer for the purpose of body movement sensing. These wearables can allow for further analysis of both an athlete’s movements and efficiency during a training drill, especially as they can provide insight on subtle differences that may not be captured without them.

Wearables enable agility to be examined in a more objective way, where slight movements and form are able to be detected, measured, and quantified. While movements of anywhere on the body may be of interest, efficiency of movement may best be represented by examination of center of mass movements (CoM). In looking into an athlete’s biomechanics, one’s Center of Mass (CoM) is defined as the location where his/her mass is distributed equally [8]. This location is commonly used to determine the stability of a person during a static or dynamic movement. Essentially we must keep the displacement and velocity of our CoM within our base of support or else we will become unstable and fall [9]. In looking at CoM in the athletic realm, it is used as a marker for measuring postural control and balance. This is not only important for enhancing performance and efficiency, but also for preventing injuries. In golfers, the CoM can be tracked throughout a swing to correct form [10]. For hurdlers and runner, studying CoM trajectories and deviations can assist a trainer in making the corrections that maximize efficiency [11-13]. While not often used in agility-related research, studying the CoM may add significant value.

As part of a larger research study, the long term goal of this work is to develop a method for predicting which individuals will prove to be high performers in an open skilled environment.
However, the specific aim for this research was to analyze the CoM movements between the pre-planned and reactive agility drill. It was hypothesized that there would be a greater deviation from an efficient path found in the reactive agility drill as a result of the added uncertainty. A secondary aim was to compare the CoM deviation in a group of poorer performers to better performers based on their pre-planned times to assess any difference between those who were faster and those who were slower. It was hypothesized that there would be a noticeable difference in CoM efficiency between those who were slower in comparison to those who were faster as this may account for some of the time difference.

Methods:

Participants:
Twenty healthy, athletic male participants were recruited from the University of Dayton's campus. All participants met the inclusion (>150 minutes of exercise per week which includes working out, running, lifting weights, or biking, and currently participating on a sports team of any level or have participated on a sports team of club level or higher within the past 4 years) and exclusion criteria (have not had a serious injury within the past 6 months, have not had a concussion within the past year, is not colorblind, has no heart conditions, does not have moderate to severe asthma, and has no current pain with physical activity). Colorblindness was an exclusion criteria as differentiating between light colors was important for the reactive agility drill. The population was as follows: ages 19 – 23 years (21 ± 1.214 years), in weight from 58.97 - 104.33 kg (79.424 ± 10.674 kg), and in height from 169 - 197 cm (180 ± 8.67 cm). A Physical Activity Readiness Questionnaire (PAR-Q) was administered after written informed consent to further clear all participants for the study [14]. The University of Dayton Institutional Review Board approved the study protocol.

Protocol:
As part of a larger research study, participants performed their pre-planned and reactive agility drills on the second (final) day of testing. Both testing days required an 8 minute warm up before advancing to the physical tests. The pre-planned and reactive agility tests followed six physical assessments and were the last two drills of the day for all participants. All participants were wearing a Zephyr bioharness band and a Xsens Awinda 17 sensor suit to record physiological and biomechanical data respectively.

For this research, the RAT test setup was amended even further to encompass a more challenging situation. The test setup mimicked a 3 meter arc with 6 Fitlights equally spaced among the arc. The center point of the arc was deemed as the starting position for all of the athletes. An example of this can be seen below in Figure 1. This newer setup increased the variability in comparison to the RAT test as there were more directional changes. Rather than just running in the direction of the illuminated light and being done, the drill required them to return to start and then run to two more lights. Fitlights allowed for researchers to program certain sequences and utilize different colors.

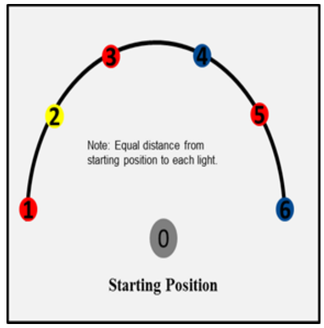

Figure 1: Test Set-up

For the pre-planned test, all participants were instructed to run to lights 1, then 3, and then 6, returning to home in between each light. This counted as one trial and three trials were completed for each subject with a 60 second break required in between. Before advancing to the reactive agility test, a 3 minute break was required in attempt to mitigate fatigue.

For the reactive agility drill, the sequence of lights was unknown to the athlete and all 6 Fitlights turned on in sync. With the concurrent lights, the sequence was programmed to utilize different colors for creating the element of visual scanning. Furthermore, all participants were instructed to run to whichever light had no color pairs, essentially the odd color light (example: 2 red, 3 green, and 1 blue). Coinciding with the pre-planned drill, there were a total of 3 lights to turn off in one trial and the participant was instructed to return to home in between each light. To add an additional stressor to the reactive agility drill, the participants were told to remember the three color sequence in order of the lights they turned off. Three trials of the reactive agility drill were ran with the same 60 second break between each trial.

Time to completion was recorded for both the pre-planned and reactive agility drill via a stopwatch. The start for each test was initiated by the researchers saying “Go” and was stopped when the athlete returned back to the starting position after the final light.

<u>Analysis:</u>
MVN 4.4 software was used in compatibility with the Xsens Awinda suit. All body movements were collected at an update frequency of 60Hz. Out of the 20 subjects, 10 subjects were used for analysis as a result of equipment malfunction or incomplete data. These 10 subjects were then divided into two groups (“above average performers” and “below average performers”) based off of their times on the pre-planned agility drills. The best trial out of the 3 was chosen for plotting and further analysis.

For determining CoM efficiency based off of the path to the light, the Xsens system provided the raw CoM positioning data in three-dimensional space over time. These values were exported into Matlab. Plots of the CoM in the forward-backward direction versus the CoM side to side direction throughout the drill were plotted in Matlab for both the pre-planned and reactive agility drills. This was done to capture the athlete's path to the three lights as they were diagonal curves. On the same plot, three straight line paths were plotted to represent the direct path to all three lights from the start, figure 2. To calculate the efficiency of staying on the linear path to the light, Sum of Squared Errors (SSE) was used. SSE was calculated by taking points on the curve (only on the path to the light) and subtracting them from points on the straight line path to the light, summing the differences for a final error. This error is essentially the area between the two paths to determine the efficiency of the athlete's movements.

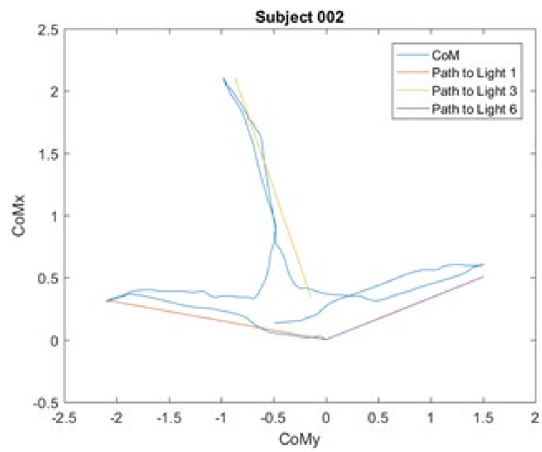

Figure 2: Example of a CoM trajectory for the Pre-planned Agility Drill

Results: Results for the ten athletes' best trial times for both the pre-planned and reactive agility drills can be seen in Table 1 below.

Table 1: Time to Completion in seconds

	Better Performers					Poorer Performers				
Pre-planned (s)	5.13	5.82	5.57	5.56	5.36	7.31	6.55	6.63	8.23	6.78
Reactive (s)	10.35	11.25	11.38	12.26	12.08	13.40	12.56	11.90	13.63	12.29

Pre-planned agility CoM plots portrayed curves that did not generally return back to (0,0) as only one foot was needed to touch start. For the reactive agility test, all subjects fully returned to the home location in order to visually assess the next light sequence. The SSE used to calculate CoM deviations from the path for the 5 good and 5 poor performers can be seen below.

Table 2: SSE for all three lights during the Pre-planned Agility Drill

	Better Performers					Poorer Performers				
Light 1	0.283	0.069	0.207	0.854	0.158	0.048	0.509	0.114	1.002	0.853
Light 2	1.943	0.682	2.327	1.304	9.372	1.170	12.95	6.845	7.097	1.617
Light 3	1.092	0.084	1.956	0.918	3.747	0.293	3.135	8.151	0.293	0.314
Average	1.106	0.278	1.497	1.025	4.426	0.504	5.530	5.037	2.797	0.928
Overall Average ± Standard Deviation				**1.66 ± 1.4349**		**2.959 ± 2.0545**				

Deviations from the path during the reactive agility drill can be seen in Table 3 below.

Table 3: SSE for all three lights during the Reactive Agility Drill

	Better Performers					Poorer Performers				
Light 1	2.163	0.062	1.407	1.884	3.398	1.087	2.381	12.711	0.911	1.802
Light 2	3.275	1.431	14.915	6.800	6.112	5.978	0.696	12.109	42.126	1.904
Light 3	10.134	1.539	2.621	29.946	1.537	0.916	0.313	1.755	15.420	4.495
Average	5.191	1.011	6.314	12.877	3.682	2.660	1.130	8.858	19.486	2.733
Overall Average ± Standard Deviation				**5.815 ± 4.1577**		**6.974 ± 7.5967**				

Discussion: The objective of this study was to analyze CoM as a biomechanical predictor of efficiency in an athlete's performance in a pre-planned versus reactive agility test; while also acknowledging that with an increase in variability, comes a decrease in efficiency. While the RAT is becoming more popular in literature, it has largely been analyzed based on time differences and has not seen enough analysis based off the biomechanical differences in comparison to the pre-planned version. Confirming CoM as a biomechanical marker to be used for efficiency analysis will allow trainers to make the proper form corrections on their open skilled athletes. This is where human monitoring systems such as wearables come into play to detect the biomechanical markers that trainers cannot see.

With time being a commonly used variable for quantifying performance, especially that of speed, it was used to break up the study population into two comparison groups: above average and below average performers. Specifically time to completion of the pre-planned agility drill was used as it did not include the variability that the reactive agility drill saw. In looking at the completion times of the pre-planned and reactive agility drill, there was an average increase in time of 84% seen for the reactive agility drill. This was expected due to the cognitive demand and uncertainty of the reactive agility drill. However, it is unclear if this change is due to the increase in processing time, inefficient movements, or a combination of factors.

In comparing the CoM deviations from the pre-planned to the reactive agility drill, the above average performers saw a 250% increase and the below average performers saw a 136% increase. While it is somewhat surprising that the above average performers were more affected by the open task, they still, on average, were more efficient than the below average performers. This may be due to a different technique approach where some athletes are programmed to run in a more curved fashion, a common defensive move, but still maintained a fast speed while doing so. Additionally the above average performers may not perform well under the cognitive load and uncertainty, whereas some below average performers were able to use their cognitive skills to make up for their lack of speed.

It is likely that the inefficiency in movement added additional time to complete the task; though this alone did not likely cause slower times. Additional information which could be captured with additional sensors, such as processing and reaction time can provide further insight to why an athlete performed differently in addition to their efficiency to the light. Furthermore, analyzing reactive agility requires more than just one factor to be examined and more wearables besides just ones that capture body biomechanics to effectively conclude results. This research attempts to dive into one of the factors of reactive agility for the benefit of future research to continue analysis on the drill.

The method for solving for the CoM deviations was not the most robust, so even though these findings follow expectations, the accuracy of the results may be questionable due to error and uncertainty within the wearable sensors. The use of the Xsens suit to predict the CoM location is dependent on accurate body dimensions, sensor placements, and the system program. Noticeable drifting or slight avatar deviations from the person warranted us to remove some subjects from further analysis, while those kept in for this analysis did not exhibit any evidence of problem, there could be some inaccuracies as well. This acknowledges some of the issues with relying on human monitoring systems and in fact the monitoring system has since been evolved to create a more robust system.

Our results do match the expectations in findings between the two groups as well as the two drills. With time to completion being an important variable in assessing an athlete's performance, decreasing the CoM deviations may present as a method for augmenting future performances. Therefore, using this biomechanical marker can provide insight into an athlete's performance and can allow for trainers to correct form and improve performances. Researchers should continue to analyze the impact of CoM in dynamic drills and the impact of efficient movements on performance.

Conclusion: Overall, results supported both of our hypotheses: higher CoM deviations were observed in the reactive agility drill and in those who were deemed as poorer performers. These results suggest that there is in fact a difference between the pre-planned and reactive agility drill besides solely the time to completion. With CoM currently being used for golfers, runners, and hurdlers, more research should be conducted to fully understand the impact it could have in augmenting athletic performance. As poorer performers generally had larger CoM deviations, fixing their form may enable faster times. However, researchers should aim to ensure their human monitoring systems are providing accurate results before making clear conclusions.

Acknowledgments: The Authors would like to thank ORISE for funding of the analysis of this project.

References:
[1] Sheppard, J. M., & Young, W. B. (2006). Agility literature review: Classifications, training and testing. *Journal of sports sciences*, *24*(9), 919-932.
[2] Arvinen-Barrow, M., Weigand, D. A., Thomas, S., Hemmings, B., & Walley, M. (2007). Elite and novice athletes' imagery use in open and closed sports. *Journal of Applied Sport Psychology*, *19*(1), 93-104.
[3] Young, W. B., & Willey, B. (2010). Analysis of a reactive agility field test. *Journal of Science and Medicine in Sport*, *13*(3), 376-378.
[4] Sheppard, J. M., Young, W. B., Doyle, T. L. A., Sheppard, T. A., & Newton, R. U. (2006). An evaluation of a new test of reactive agility and its relationship to sprint speed and change of direction speed. *Journal of science and medicine in sport*, *9*(4), 342-349.
[5]Young, W., & Rogers, N. (2014). Effects of small-sided game and change-of-direction training on reactive agility and change-of-direction speed. *Journal of sports sciences*, *32*(4), 307-314.
[6]Scott, W. A. (1962). Cognitive complexity and cognitive flexibility. *Sociometry*, 405-414.
[7]Mukhopadhyay, S.C. (2015). Wearable sensors for human activity monitoring: A review: *IEEE Sensors Journal*, 15(3), 1321-1330. Chicago.
[8]Boundless. "Center of Mass." *Center of Mass | Boundless Physics*, courses.lumenlearning.com/boundless-physics/chapter/center-of-mass/.
[9]Yamaguchi, T., Higuchi, H., Onodera, H., Hokkirigawa, K., & Masani, K. (2016). Misalignment of the desired and measured center of pressure describes falls caused by slip during turning. *PloS one*, *11*(5), e0155418.
[10]Najafi, B., Lee-Eng, J., Wrobel, J. S., & Goebel, R. (2015). Estimation of center of mass trajectory using wearable sensors during golf swing. *Journal of sports science & medicine*, *14*(2), 354.
[11]Krzeszowski, T., Przednowek, K., Iskra, J., & Wiktorowicz, K. (2015). Monocular Tracking of Human Motion in Evaluation of Hurdle Clearance. 16-29. 10.1007/978-3-319-25249-0_2.
[12]Bollschweiler, L. R. (2007). A biomechanical analysis of male and female intermediate hurdlers and steeplechasers.

[13]Gindre, C., Lussiana, T., Hébert-Losier, K., & Mourot, L. (2016). Aerial and terrestrial patterns: a novel approach to analyzing human running. *International journal of sports medicine*, *37*(1), 25-29.
[14] Bredin, S. S., Gledhill, N., Jamnik, V. K., & Warburton, D. E. (2013). PAR-Q+ and ePARmed-X+: new risk stratification and physical activity clearance strategy for physicians and patients alike. *Canadian family physician*, *59*(3), 273-277.