Real-Time Optical Motion Capture Balance Sonification System

Graduate Symposium[†]

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ABSTRACT

In this study, we explored the effects of a motion capture-based real-time sonified biofeedback system on balance. We present the initial efforts towards developing a task-independent optical motion capture based real-time balance sonification system. Five healthy young adults (two female; 24 ± 2.65 years) stood on one foot before and during listening to sonified biofeedback that expressed information in real-time about the state of their balance. In two of five participants, interacting with our sonified biofeedback system resulted in increased "Margin of Stability", a metric indicative of how well the body center of mass is supported by a person's stance. This result indicates our system's initial promise towards training balance strategies. Qualitatively, the participants who increased the Margin of Stability during sonification reported enjoying the experience more and were more aware of changes in their behavior, compared to those who did not increase their Margin of Stability. We also learned that our sonification system has design elements that are incompatible with the stationary tasks in the present study, which will inform our next iteration of sonification design. Future work will examine sonifying balance in dynamic balance tasks, with the goal of aiding clinical balance training.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Empirical studies in HCI* • **Human-centered computing → Human computer interaction (HCI)**; *Interaction devices →* Sound-based input/output

KEYWORDS

Biomechanics, Balance, Sonification

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1 INTRODUCTION

1.1 Clinical Importance of Balance

The human bipedal anatomy is inherently unstable, requiring active balance control to stay upright while moving. If balance is not maintained, a fall will occur. Fall-related injuries due to loss of balance are a leading cause of injury and mortality for older adults [1]. For some, the practice of balancing during everyday tasks is not sufficient to stay upright. Transitional movements such as turning while walking are especially difficult for some populations, such as the elderly and those with Parkinson's disease. To remain independently mobile, clinical balance training with a physical therapist or through the use of an assistive technology with external biofeedback may be required.

1.2 Sonified Biofeedback for Clinical Purposes

Sonification, which maps real-time measurements through sound, has recently become of clinical interest. We aim to use audio biofeedback to benefit balance for the dual advantages of allowing natural visual flow and leveraging anatomical connections between the audio and motor systems. Sonification has been used in many clinical contexts, for example [2-10]. Existing systems

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have been shown to assist balance specifically in static upright stance [11]. We aim to develop a real-time motion capture-based balance assistance sonification system for use across multiple types of tasks. We are in the initial stages of developing this system, building on previous works [11,12].

We are currently testing how a prototype sonified biofeedback system affects the way young healthy adults perform static balance tasks. Next, we will test how sonified biofeedback affects the way young healthy adults perform dynamic balance tasks, with an emphasis on transitional movements like turns. The current iteration of this system sonifies Margin of Stability (MOS) [13], base of support (BOS) area, and total body center of mass (TBCM) location relative to BOS boundaries. We hypothesize that when performing a single leg static balance task, providing sonified biofeedback of balance metrics will increase the MOS compared to before biofeedback in young healthy adults.

2 METHODS

2.1 Participants

Five participants (two female; age 24 ± 2.65 yrs) volunteered for this study. All participants self-identified as being without balance deficits, hearing loss, or comorbidities that prevent them from participating in exercise.

2.2 Testing Procedure

After providing informed consent, participants performed five trials of one-minute stationary single leg stance, repeated Before and During sonified biofeedback. Verbal instructions with accompanying audio, as well as free movement time to explore the sound design, were provided for participants to practice moving with the sound. They also completed conversational interviews and online surveys asking about their opinions of the sound, interacting with it, how understandable it was, and what they liked and disliked about it.

2.3 Motion Capture Instrumentation

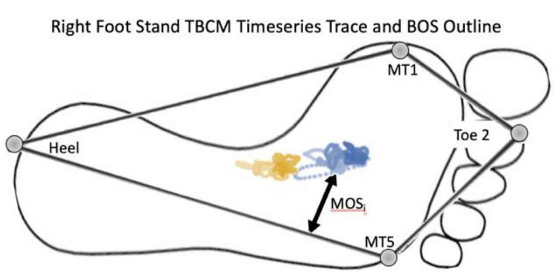

Figure 1: Representative (Subject 4) TBCM trajectories Before (yellow) and During (blue) sonified biofeedback, shown on a right foot BOS convex hull. Light to dark indicates forward progression of time. MOS is labelled at one timepoint. Labelled gray circles are motion capture markers; foot illustration is included for reference.

A 12-camera optical motion capture system (Optitrack, OR) streamed labelled three-dimensional marker position data at 360Hz to a custom MATLAB (Mathworks, MA) program via Optitrack's "Natnet" streaming protocol. MATLAB processed the 3D marker data into balance metrics, which were then streamed via Open Sound Control protocol to MaxMSP (Cycling '74, CA) for sonification. Preliminary estimation of the system's latency is approximately 50ms (20Hz), based upon testing within MATLAB only.

Reflective markers (BL Eng., IN) were placed on the entire body per Optitrack's "39 Marker Full Body Conventional" marker set, with markers added to the medial elbow, knees, and ankles to determine the proximal and distal endpoints of each body segments. We also added markers to the first and fifth metatarsals and the tip of the second toe to better match the base of support convex hull to the outline of the foot (Fig. 1).

2.4 Computation of Balance Metrics

Three balance metrics were sonified. First, the margin of stability (MOS) was computed as the horizontal distance between the total body center of mass (TBCM) and the closest edge of the base of support (BOS) convex hull (defined by foot markers in contact with the ground). The biomechanics of maintaining static balance requires that the TBCM is horizontally within the BOS (MOS > 0). The TBCM was computed as the weighted sum of all body segments' center of mass locations [14]. Second, the boolean value of whether it was inside or outside of the BOS convex hull was also sonified (1 if within the BOS). Third, the BOS area (computed by MATLAB's 'boundary' function) was sonified.

For statistical analysis, within-subject Cliff's analog of the Wilcoxon-Mann-Whitney test [15] was used to compare mean, median, and max MOS Before vs. During biofeedback (α=0.05).

2.5 Sonification Design

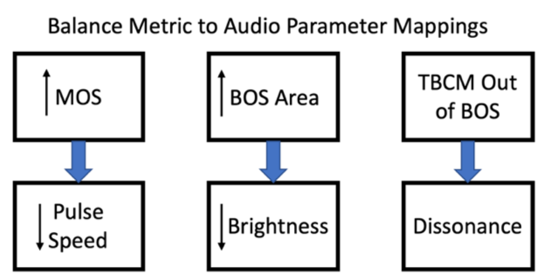

Figure 2: Balance metric to audio parameter mappings. As MOS or BOS area increase, pulse speed or brightness decreased, respectively. If TBCM was in the BOS, dissonance was off. Dissonance toggled on when TBCM was outside of the BOS.

The sound generation consists of two oscillators whose outputs are each sent through a band-pass filter, then summed and followed by a gain. The sound can be varied according to three parameters: pulse speed, brightness, and dissonance. Pulse speed varies the periodic rate at which the gain and filters are modulated; brightness controls the average center frequency of the filters; dissonance controls the relative tuning of the two oscillators. Pulse speed and brightness mappings were scaled from 0 to 1 such that the entire range was achievable during the single leg stance task.

Margin of stability was mapped to pulse speed (Fig. 2) such that as the TBCM moved closer to the BOS convex hull (lower MOS) the pulse speed increased closer to 1 (faster pulse speed). This mapping aimed to impart a sense of urgency about moving away from the BOS boundaries, while the very slow pulses when the TBCM was at the center of the BOS indicated relative safety from falling.

Next, BOS convex hull area mapped inversely to brightness; larger BOS areas resulted in lower brightness, smaller BOS areas resulted in higher brightness (Fig. 2). Higher brightness is less pleasant to listen to, therefore the sound emphasized maintaining a larger base of support, which we thought to be more conducive to balance in static tasks. Finally, the boolean value of whether TBCM was within (1) or outside (0) of the BOS convex hull was mapped to the dissonance of the system. If the boolean was 0, there was no dissonance. But if TBCM was outside the BOS boundary (boolean=1), dissonance was introduced to the audio.

3 RESULTS AND DISCUSSION

3.1 Effects of Sonification on Balance Metrics

During biofeedback, two of five participants significantly increased their maximum, mean, and median (Fig. 3) MOS compared to Before biofeedback (p=0.032 for all three metrics and both subjects). No subjects displayed the opposite trend between conditions. BOS area was constant throughout given the nature of the single leg stance task. Additionally, the TBCM was only outside of the BOS boundary at any time for Subject 2.

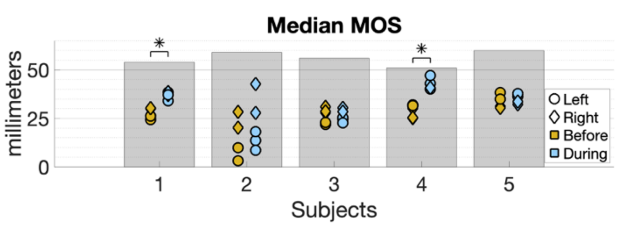

Figure 3: Median MOS in Before (yellow) and During (blue) sonified biofeedback conditions for each subject during single leg stance of the left (circles) and right (diamonds) legs. Gray bars display the range (minimum to maximum) of possible MOS values for each subject's base of support geometry.

Our hypothesis was partially supported by significant changes in two of five subjects' median (Fig. 3), mean, and maximum MOS. It is unclear why the other three participants did not change their MOS in response to the audio biofeedback. Participant 2 differed from the others in that they exhibited a much wider range of median MOS values across trials (Fig. 3), but the range of Participants 3 and 5's median MOS values do not appear to be the reason for their non-response to the audio. To help answer that question, we looked to their interview and survey responses.

It is unclear whether the MOS changes we observed are practically significant as the TBCM movement is small relative to the BOS size (Fig. 1). Further, maximizing MOS in single-leg stance may not be functionally helpful as it requires the TBCM to be more anterior, closer to the forefoot. Despite the maximum MOS decreasing, posterior TBCM placements can take advantage of underlying musculoskeletal structure that may reduce the need for active balance control.

Also, due to the differences observed between right and left stance legs (Fig. 3 circles vs. diamonds), future single leg balance research will be restricted to comparisons of the right or left leg support separately. We also acknowledge that our current BOS model may be biased medially relative to the foot surface (as in Fig. 1).

3.2 Preliminary Interview and Survey Results

3.2.1 Interview Responses. The two "positive respondents", those that significantly improved their median MOS (Participants 1 and 4, Fig. 3), shared positive feedback about their experiences moving with the audio, stating that they "liked it" and it was "pretty cool", "relaxing", "consistent", and "very accurate". They also indicated conscious understanding that the audio had affected their balance, stating "the more I understood, the more I explored the limits of my balance" and that "I was definitely using the feedback".

3.2.2 Survey Responses. The positive respondents shared similar sentiments in their written surveys as in the conversational interviews. They liked that the changes were "distinct and easy to understand" and how "quick and accurate" they perceived it to be. Participant 1 reported using the changes in pulse speed the most. Their opinion of the sound overall was "neutral" but "helpful", and from a word bank described it as "forceful".

Participants that did not integrate the sound into increased MOS were less positive in their responses. Participant 2 felt that the "sound was too neutral, very easy to tune out" and thought the sound "harsh". Participants 3 and 5 felt the sound was "rough" and also stated that they realized that they were unable to make sense of the audio biofeedback to increase their MOS. Specifically, Participant 5 noted "I changed methods of keeping balance but then stopped when I couldn't improve my balance." While the two positive respondents rated the audio as "forceful" from the word bank, the other three did not.

3.3 Lessons Learned About Sonification Design

This section describes observations and take-home lessons learned from the process of building and testing the sonification system. It also outlines guiding principles to observe and future avenues of exploratory study to pursue.

3.3.1 Sound Generation. Comparisons of experimenter observation and participant feedback between pilot testing and this study revealed the importance of carefully considering the timbral properties of sound design, even when maintaining the same balance metric to audio parameter mappings. We noted that changes in timbral properties of the brightness parameter resulted in much clearer audio changes as the BOS changed. This underscores the importance of the particular timbral effect of each individual audio parameter. We will also explore the relationship between audio perception and MOS changes.

3.3.2 Movement Parameter Scaling. During pilot testing, participant-specific scaling of movement parameters was used to ensure that all participants heard relatively similar audio. However, that was observed to be insufficient as tasks that required dissimilar BOS convex hull geometries from the calibration stance experienced poor audio biofeedback discernibility. We then switched to a person and task-specific parameter scaling scheme for this study. MOS is now scaled to the maximum MOS computed for that task's BOS geometry (height of gray bars, Fig. 3), while BOS area was scaled by that geometry's area. This provided more qualitatively discernible changes in audio as balance metrics changed but has the drawback of requiring calibration trials for each task (vs. one calibration per participant). Although task-specificity is less relevant when only one task is being performed, throughout a series of studies we will improve upon this system to encompass many task types, including dynamic tasks such as turning while walking. Therefore, we may be able to build a framework to extrapolate task-specific ranges given a model of each person's foot.

3.3.3 Sonification Design Questions. We have taken a different approach than previous sonification designs for balance training e.g. [16-20]. Iterative testing will likely reveal some balance metrics and audio parameter combinations that affect balance more than others. In the current case of a static balance task, mechanics seems to dictate that MOS is a logical balance metric to monitor because the requirement for maintaining static balance is that the TBCM falls within the BOS (MOS > 0). Quantitative and qualitative outcomes from the two positive respondents also most strongly support the choice of this balance metric.

However, during static balance tasks, there may not be as clear of a rationale for sonifying the BOS area or TBCM location Boolean balance metrics. BOS area may be a more useful indicator of when the BOS changes during dynamic tasks. Similarly, no participant mentioned the effects of sonifying the TBCM, likely due to the fact that it remained within the BOS for most trials tested thus far. If these results continue as our studies expand, this could seem to implicate choosing to remove or replace this Boolean balance metric during static balance tasks in the future.

4 CONCLUSIONS

This work builds upon initial efforts at developing a task-independent optical motion capture-based real-time balance sonification system. This preliminary study indicates initial promise towards the system's ability to increase MOS. Increased MOS is one of many balance metrics used clinically to quantify balance control. In the future, we will expand our focus and the capabilities of this system to encompass multiple dynamic tasks as well as accommodate different populations with balance deficits. Our long-term goal is to implement this technology in clinical applications.

REFERENCES

[1] Stevens, J. A., Mack, K. A., Paulozzi, L. J., & Ballesteros, M. F. (2008). Self-Reported Falls and Fall-Related Injuries Among Persons Aged ≥ 65 Years-United States, 2006. *Journal of Safety Research*.

[2] Gorgas, A. M., Schön, L., Dlapka, R., Doppler, J., Iber, M., Gradl, C., … Horsak, B. (2017). Short-Term Effects of Real-Time Auditory Display (Sonification) on Gait Parameters in People with Parkinsons' Disease—A Pilot Study. In *Biosystems and Biorobotics*.

[3] Hasegawa, S., Ishijima, S., Kato, F., Mitake, H., & Sato, M. (2012). Realtime sonification of the center of gravity for skiing. *ACM International Conference Proceeding Series*.

[4] Costantini, G., Casali, D., Todisco, M., Saggio, G., Giansanti, D., & Maccioni, G. (2015). Towards the improvement of postural stability through audio bio-feedback. *WISP 2015 - IEEE International Symposium on Intelligent Signal Processing, Proceedings*, (June).

[5] Fleszar, Z., Mellone, S., Giese, M., Tacconi, C., Becker, C., Schöls, L., … Ilg, W. (2019). Real-time use of audio-biofeedback can improve postural sway in patients with degenerative ataxia. *Annals of Clinical and Translational Neurology*, *6*(2), 285–294.

[6] Scholz, D. S., Rohde, S., Nikmaram, N., Brückner, H. P., Grobbach, M., Rollnik, J. D., & Altenmüller, E. O. (2016). Sonification of arm movements in stroke rehabilitation - a novel approach in neurologic music therapy. *Frontiers in Neurology*, *7*(JUN), 1–7.

[7] Mirelman, A., Herman, T., Nicolai, S., Zijlstra, A., Zijlstra, W., Becker, C., … Hausdorff, J. M. (2011). Audio-biofeedback training for posture and balance in patients with Parkinson's disease. *Journal of NeuroEngineering and Rehabilitation*.

[8] Nicolai, S., Mirelman, A., Herman, T., Zijlstra, A., Mancini, M., Becker, C., … Maetzler, W. (2010). Improvement of balance after audio-biofeedback. A 6-week intervention study in patients with progressive supranuclear palsy. *Zeitschrift Fur Gerontologie Und Geriatrie*.

[9] Dubus, G. (2012). Evaluation of four models for the sonification of elite rowing. *Journal on Multimodal User Interfaces*.

[10] Chow, D. H. K., & Cheng, C. T. K. (2000). Quantitative analysis of the effects of audio biofeedback on weight-bearing characteristics of persons with transtibial amputation during early prosthetic ambulation. *Journal of Rehabilitation Research and Development*, *37*(3), 255–260.

[11] Schaffert, N., Janzen, T. B., Mattes, K., & Thaut, M. H. (2019). A review on the relationship between sound and movement in sports and rehabilitation. *Frontiers in Psychology*.

[12] Dahl, L., Knowlton, C.B., Zaferiou, A. (2019). Developing real-time sonification with optical motion capture to convey balance-related metrics to dancers. *ACM International Conference Proceeding Series*, *1*

[13] Hof, A. L., Gazendam, M. G. J., & Sinke, W. E. (2005). The condition for dynamic stability. *Journal of Biomechanics*.

[14] Cliff, N. (2014). Ordinal Methods for Behavioral Data Analysis. In *Ordinal Methods for Behavioral Data Analysis*.

[15] De Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia paremeters. *Journal of Biomechanics*, *29*(9), 1223–1230.

[16] Bevilacqua, F., Peyre, I., Segalen, M., Pradat-Diehl, P., Marchand-Pauvert, V., & Roby-Brami, A. (2018). Exploring different movement sonification strategies for rehabilitation in clinical settings. *ACM International Conference Proceeding Series*.

[17] Effenberg, A. O. (2005). Movement sonification: Effects on perception and action. *IEEE Multimedia*.

[18] Cook, P. R. (2011). Sound synthesis and auditory display. In *The Sonification Handbook*.

[19] Neuhoff, J. G. (2011). Perception, Cognition and Action in Auditory Displays. *The Sonification Handbook*.

[20] Walker, B., & Nees, M. A. (2011). Theory of Sonification. In *The Sonification Handbook*.

[21] Dyer, J. F., Stapleton, P., & Rodger, M. W. M. (2017). Advantages of melodic over rhythmic movement sonification in bimanual motor skill learning. *Experimental Brain Research*, *235*(10), 3129–3140.

[22] Dyer, J. F., Stapleton, P., & W. M. Rodger, M. (2016). Sonification as Concurrent Augmented Feedback for Motor Skill Learning and the Importance of Mapping Design. *The Open Psychology Journal*, *8*(1), 192–202.