Evaluation of Visual Biofeedback Modalities for Running Gait Retraining Using a Low-Cost Motion Capture System

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Abstract. *Modifying running biomechanics helps optimize movement and reduce joint stress. This preliminary study evaluated the feasibility of two real-time visual biofeedback methods using a low-cost optical motion capture system. In a crossover design, four participants tested a vertical displacement graph interface and an animation interface for cadence synchronization. The results indicate that the graphical biofeedback obtained greater acceptance and ease of immediate motor adaptation. In contrast, the rhythmic interface required greater cognitive demand, generating frustration. Future work will integrate auditory stimuli and adjustments to the test protocol.*

1. Introduction

The biomechanical analysis of human running frequently utilizes the spring-mass model to describe the interaction between the body and the ground. In this model, movement efficiency depends on the balance between vertical oscillation and the capacity for elastic energy storage. It is observed that excessive oscillations result in energy waste, whereas excessively low oscillations compromise the reuse of elastic energy in the tendons, raising the metabolic cost (Schubert et al., 2014).

Beyond the vertical component, cadence is a central variable in modulating impact loads. The literature indicates that increasing step frequency is an effective strategy for reducing excessive stride length, or overstriding, which is associated with increased braking impulse and joint stress in the lower limbs (Heiderscheit et al., 2011; Napier et al., 2015). Thus, cadence adjustment acts as an indirect mechanism for postural alignment and the mitigation of impact forces.

Real-time biofeedback systems emerge as tools to promote motor retraining and the consolidation of more efficient biomechanical patterns. However, the efficacy of these interventions is conditioned by the cognitive load imposed on the individual. The sudden imposition of targets too far from the subject's natural pattern can generate the dual-task interference phenomenon, where the attempt to process the external visual stimulus competes with intrinsic motor control. Excessively ambitious targets result in constant tracking failures, generating frustration and hindering motor learning (Agresta and Brown, 2015). This study investigates the feasibility and usability of a low-cost optical motion capture (MoCap) system to provide two modalities of biofeedback. The objective is to evaluate how participants respond to spatial signaling (vertical oscillation) compared to rhythmic signaling (cadence synchronization), observing the acute adaptation capacity and the signs of cognitive overload inherent to each interface.

2. Related Work

The manipulation of cadence and the reduction of vertical oscillation are established strategies to mitigate running impact (Heiderscheit et al., 2011; Schubert et al., 2014).

When investigating these variables, Adams et al. (2018) found that focusing on restricting vertical oscillation is more efficient in decreasing peak vertical ground reaction force, whereas increasing cadence acts more effectively in reducing the braking impulse. Their distinct impact absorption profiles justify simultaneous investigation to identify the best clinical intervention.

To obtain biomechanical data, although the literature frequently utilizes commercial accelerometers (Adams et al., 2018), the use of marker-based optical systems provides the absolute displacement of the tracked position. This methodological approach, proposed in this study, ensures positional precision for real-time biofeedback generation, as the optical system tracks displacement directly, avoiding the drift errors associated with the double mathematical integration inherent to inertial sensors.

Regarding the sensory modality, a recent systematic review (Shen et al., 2024) demonstrated the superiority of visual biofeedback over auditory biofeedback in the immediate alteration of impact variables. This advantage is due to the graphical interface's capacity to enable continuous and detailed corrections, unlike the auditory stimulus, which acts restricted to rhythmic adjustment. However, this wealth of information imposes a greater cognitive demand on the runner. Therefore, this study proposes the evaluation of two visual biofeedback formats (spatial versus rhythmic) via low-cost optical capture, aiming to determine which interface promotes the expected biomechanical adaptation with less attentional interference, in addition to validating the system's technical applicability in gait retraining.

3. Methodology

3.1 Participants, Equipment, and Marker Placement

The study included four adult male participants, all regular runners. The anthropometric characteristics of the sample are detailed in Table 1.

Table 1 - Anthropometric characteristics of the participants.

Participant	Age (years)	Body Mass (kg)	Height (cm)	Leg Length (cm)
1	46	69	181	95.0
2	33	78	184	95.5
3	44	68	174	89.6
4	54	66	171	89.2

A motion capture system with four OptiTrack V100 cameras, operating at 100 frames per second, was utilized. Although produced by a professional manufacturer, the model used represents the simplest and most affordable camera in its category, with only VGA resolution (640x480), but with sufficient precision for the intended purpose. Kinematic tracking employed three reflective markers: one on the posterior region of each shoe (for determining cadence and impact moments) and one on the L5 lumbar vertebra region (for detecting vertical displacement and estimating the center of mass).

3.2. Biofeedback Modalities

Two visual biofeedback interfaces were evaluated and displayed on a 43-inch 4K television positioned frontally to the participant: **(A) Vertical Displacement Biofeedback**: a continuous graph of the lumbar marker's vertical position was used alongside a green demarcating line, calibrated to represent a 10% reduction in the mean vertical oscillation obtained at baseline. The instruction was to keep the graph's peaks below this mark (Figure 1-A); **(B) Cadence Biofeedback**: simulated a vertical treadmill with descending footprints, adjusted to a speed 10% higher than the runner's baseline cadence. The participant was instructed to synchronize the actual footfall impact with the exact moment the virtual footprint crossed the central target line on the screen (Figure 1-B).

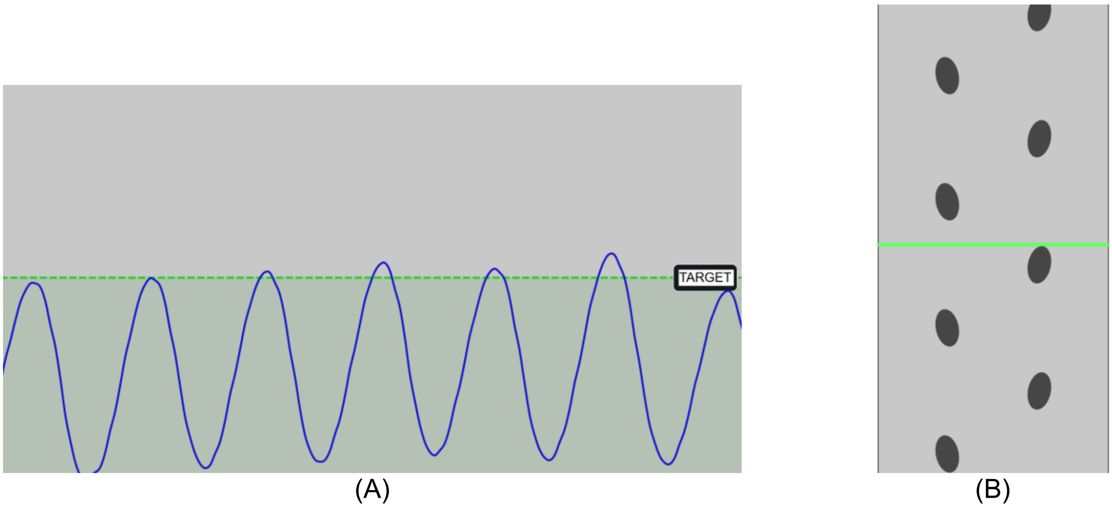

Figure 1 - Evaluated visual biofeedback modalities: (A) – Vertical displacement biofeedback interface; (B) – Cadence biofeedback interface (step synchronization).

3.3. Experimental Protocol

A crossover design was adopted to mitigate order effects. The sample was divided into two groups, alternating the initial biofeedback. The protocol lasted 20 minutes, structured into the following phases: (1) three minutes of pre-warm-up walking at 6 km/h; (2) three minutes of warm-up running at 10 km/h; (3) three minutes of running at 10 km/h to record natural parameters (baseline); (4) three minutes of intervention with the first biofeedback modality at 10 km/h; (5) five minutes of walking at 5 km/h (washout); and (6) three minutes of intervention with the other biofeedback modality.

3.4. Implementation Aspects

The software was implemented using C# under an asynchronous multithreaded architecture. To synchronize the optical capture and visual display, the rendering loop operated independently of the data acquisition thread, ensuring non-blocking real-time processing with a latency under 20 ms. Signal processing employed a 4th-order Butterworth digital low-pass filter to mitigate noise inherent to the system. The interface was developed using the GDI+ library. For the graphical curve, an **E**xponential **M**oving **A**verage (EMA) filter was utilized for visual smoothing.

4. Results and Discussion

The analysis of the three-dimensional coordinate files obtained during the experiment indicates an alteration in the biomechanical pattern of all participants during the application of the biofeedback, as presented in Table 2. The results indicate that both modalities could promote immediate kinematic adjustments, with reductions in vertical oscillation and increments in cadence relative to baseline values.

Particip.	Baseline Cadence (spm)	Baseline Oscillation (mm)	Cadence with Biofeedback A (spm)	Oscillation with Biofeedback A (mm)	Cadence with Biofeedback B (spm)	Oscillation with Biofeedback B (mm)
1	157	64	171	51	165	53
2	154	64	170	52	170	44
3	166	59	182	48	181	46
4	178	51	202	38	182	47

Table 2: Mean kinematic metrics per phase.

Figure 3 compares the lumbar vertical displacement (L5 marker) of Participant 1. The graph superimposes the natural baseline oscillation (gray color) onto the one recorded under biofeedback intervention (blue color). The dashed lines delimit the 10% amplitude reduction target. Gait stabilization within this restrictive range demonstrates the subject's motor adaptation, attesting to the interface's efficacy in modulating kinematics in real time.

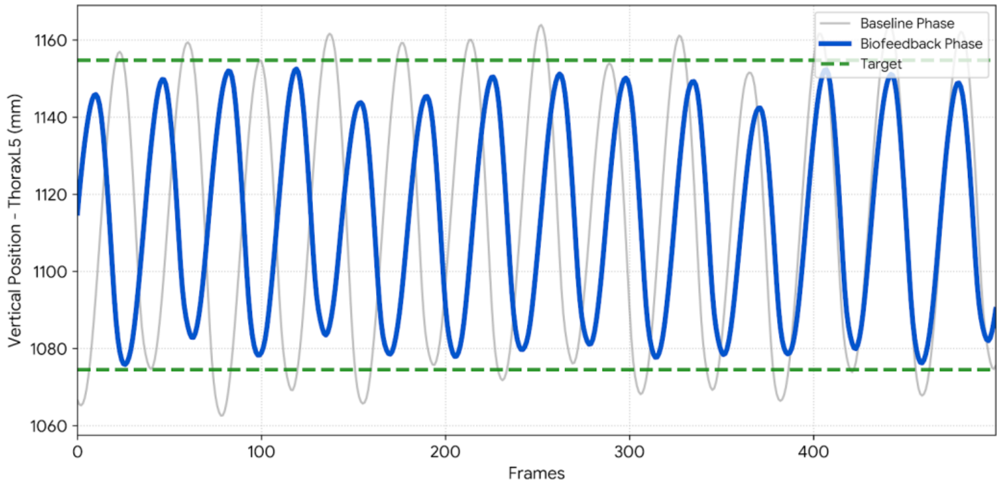

Figure 3: Comparison of vertical displacement (Participant 1).

The data corroborate the literature (Heiderscheit et al., 2011) regarding the inversely proportional relationship between step frequency and vertical excursion. Visual stimuli directed at lower limb mechanics altered both metrics, regardless of the interface. However, differences were observed in the assimilation of each format. Participants 3 and 4 had trouble with the cadence biofeedback: although they reached the target numerical value, they could not sustain rhythmic synchronization for a prolonged period, evidencing frustration. The remaining participants adapted stably after a learning curve of approximately 30 seconds. This instability is linked to the required 10% increment. Established to maximize acute adaptations within three minutes, this value exceeds the conservative margin of 5% to 7.5% recommended to contain the initial metabolic cost (Heiderscheit et al., 2011; Schubert et al., 2014; Willy et al., 2016). The association of this physical requirement with the high attentional demand of the rhythmic interface justifies the difficulties faced by part of the sample. In contrast, the vertical displacement biofeedback proved more intuitive. Participants kept their oscillation below the target most of the time. By imposing a static spatial constraint, this interface provides the motor system with the freedom to self-regulate step frequency and length, facilitating motor execution.

Finally, the variability in absolute vertical oscillation among subjects (Table 2) stems from anthropometric differences. Given that this study focused on acute intrasubject effects, efficacy was attested by relative variations. Future analyses with larger samples will standardize the data through the normalization of displacement by lower limb length.

5. Conclusion

The integration of a low-cost optical motion capture system with asynchronous processing in C# proved to be technically feasible and effective in the acute modulation of running kinematics. A latency under 20 ms ensured the real-time perception required for immediate motor adjustments. The graphical vertical displacement biofeedback achieved higher acceptance than the visual cadence synchronization. This result indicates that spatial constraints provide a biomechanical adaptation with a lower and more tolerable cognitive demand compared to that imposed by the rhythmic visual task.

Methodological refinements will be adopted in future work with larger samples. The cadence interface will be optimized to mitigate attentional demand, and rhythmic auditory biofeedback (metronome) will be integrated to evaluate whether the auditory pathway requires less adaptive effort compared to the proposed visual formats. Furthermore, running speed will be reduced to 9 km/h and cadence increment targets will be adjusted to the 5% to 7.5% range. These modifications aim to mitigate acute physical overload, allowing for a more precise isolation and observation of the cognitive cost inherent to each interface.

6. References

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