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AUFLIP
Teaching Front Flips with Auditory Feedback Towards a System for Learning Advanced Movement

DANIEL VISAN LEVINE

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ABSTRACT

AUFLIP describes an auditory feedback system approach for learning advanced movements, informed and motivated by established methods of implicit motor learning by analogy, our physiological constraints, and the state of the art in augmented motor learning by feedback. AUFLIP presents and validates a physics simplification of an advanced movement, the front flip, and details the implementation of a wearable system, optimized placement procedure, and takeoff capture strategy to realize this model. With an audio cue pattern that conveys this high level objective, the system is integrated into a gymnastics training environment with professional coaches teaching novice adults how to perform front flips. A strategy, system, and application set building off AUFLIP for more general movement, and applications is further proposed. Lastly, this work performs a preliminary investigation into the notion of Audio-Movement Congruence, and whether audio feedback for motor learning can be personally tailored to individuals’ contextual experiences and background, and explores future applications of the discussed systems and strategies.

Thesis Supervisor:
Professor Hiroshi Ishii
Jerome Weisner Professor of Media Arts and Sciences
Program in Media Arts and Sciences
The following people served as readers for this thesis:

**Signature redacted**

Thesis Reader......
Leia Stirling
Assistant Professor
Charles Stark Draper Professor of Aeronautics and Astronautics
MIT Department of Aeronautics and Astronautics

**Signature redacted**

Thesis Reader......
Sangbae Kim
Associate Professor
MIT Department of Mechanical Engineering
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INTRODUCTION

1.1 LEARNING NEW MOVEMENTS

Human movement spans an amazing breadth. From our ability to walk to perform acrobatics, we are capable of learning and experiencing a wide breadth of perspectives and experiences.

Achieving these motions with little related experience, however, is no easy feat. Either they are achievable in youth with training, or require significant time, effort, and courage to develop the confidence and understanding to perform well. Learning new movements for the first time in new cognitive and physical environments is difficult.

The author of this work comes from a background of gymnastics, and has experienced the challenge of teaching newcomers how to become comfortable learning various different motions in gymnastics. In particular, the author finds that many struggle learning the skill of performing a front flip. While the motion is not particularly complex, it takes place in a very unfamiliar physical and cognitive space. This work presents and tests a strategy towards helping people build procedural knowledge for these kinds of movements - knowledge that sticks with people - using auditory feedback driven by high-level goals.

![Calvin and Hobbes: Learning Unfamiliar Movement](image)

Figure 1: Calvin and Hobbes: Learning Unfamiliar Movement

1.2 THESIS CONTRIBUTIONS

This thesis first looks at previous work in learning to outline implicit and explicit learning and the methods required to achieve implicit learning. Then we examine previous methods of providing feedback for motor learning, especially with regards to auditory feedback. Supported by this related work, we outline and propose a strategy for providing auditory feedback for implicit learning, and detail the im-
plementation of this system. We test this system with novices learning how to front flip for the first time alongside professional coaching, and use the results as directions for future work; how to generalize this feedback system to be useful beyond an aid for front flips and how to create sound-based analogies for movement via an initial foray into a notion of audio-movement congruence.

1.2.1 Thesis Outline

From this strategy, we break down this work into the following parts:

2 examines previous work regarding techniques for motor learning; timing, feedback, evaluation of performance results. It looks at more recent work done examining in particular, explicit vs. implicit learning, and techniques that make use of obscured feedback to achieve implicit learning and development of procedural knowledge.

3 outlines our approach and design decisions for an auditory-feedback system for aiding novice athletes to perform advanced movements.

4 describes in detail a case study implementation of an auditory feedback system for a rapid dynamic motion. This system describes design choices, methods and validation for choice of physics model and wearable sensor device.

5 describes a user study performed using the implemented system, training adult newcomers who have never engaged in gymnastics or front flips prior to perform front flips. This study mostly examines the process of training, with some evaluations of the feedback system and discussion of its possible role in training persons in unfamiliar skills.

6 proposes future expansions of the present work for various forms of movement outside of the gymnastics front flip case study. 6 also conducts an initial exploration into the notion of Audio-Movement Congruence towards being able to craft and integrate customized sound analogy profiles for auditory feedback.

7 provides concluding remarks on this thesis and the proposed future work.

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• David Olayeye - Contributed towards Audio Movement Congruence ideas and prototyping in 6.

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• Mohammed Aamir - Contributed towards the original ideas regarding flip physics during the beginning stages of this work.

• Luke Hyman - Reviewed this thesis and contributed towards paper structure and clarity.

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RELATED WORK

To begin, this chapter examines definitions of motor learning, methods of evaluation for motor learning, strategies for motor learning, and effective delivery of feedback for motor learning. We examine further in depth past findings on the topics of implicit and explicit learning and augmented feedback, as they relate to our goal of helping people implicitly learn advanced, unfamiliar motions.

2.1 MOTOR LEARNING

Schmidt and Lee define motor learning as "...a set of processes associated with practice or experience leading to relatively permanent gains in the capability for skilled performance."[37]

Various different perspectives govern motor learning. Fitts and Bernstein highlight two overall schools of thought; motor learning from an information processing perspective, and motor learning from a biomechanical perspective.

2.1.1 Fitt’s Stages of Perceptual-Motor Learning

In Stage 1 – the Cognitive Stage, learners define the problem they are trying to solve. They tend to formulate questions, trying to understand their environment, developing a goal, and attempting a movement pattern. In Stage 1, very direct instructional videos are most helpful. In Stage 2 – the Fixation Stage, learners have developed an adequate understanding of their environment and goal and focus on developing a more effective movement pattern; attention becomes more focused towards motion. In Stage 3 – the Autonomous Stage, learners have developed expert performance, minimizing need to focus on movement patterns, and freeing up resources to anticipate and process information from the environment. [18]

2.1.2 Bernstein’s Stages of Motor Learning – A Biomechanical Perspective

In Bernstein’s Stage I, learners first attempt to simplify motion by reducing degrees of freedom by stiffening or locking out the body. In Bernstein’s Stage II, learners release degrees of freedom, enabling some use of passive dynamics to enable greater power and speed. In Bernstein’s Stage III, learners exploit and understand how to manipu-
late their body’s passive dynamics, enabling maximum effectiveness and efficiency. [6]

2.1.3 Schema Theory

Schema theory states that particular skills and motions maintain some basic fundamental characteristics. As learners become more proficient at the skill or motion, they learn variations - "schemes" - that become applied to these base fundamental characteristics.[36] As an example, gymnasts may learn fundamental basic circle movement and swings on the pommel horse; as they encounter various situations and advanced maneuvers they apply various schemes that affect the motion and their unarticulated understanding of their interaction with the environment. Schema learning typically benefits from random, or variable practice.[36]

2.1.4 Methods of Evaluating Learning

2.1.5 Rasmussen’s Levels of Performance

To aid in the design of human-machine interfaces, Rasmussen characterized human performance into three levels; skill based behavior, rule based behavior, and knowledge based behavior. Skill-based behavior does not require conscious attention and tends to be “smooth, automated, and highly integrated.” Skill-based behavior includes riding a bicycle, or playing an instrument. Rule-based behavior describes some conscious attention; rule-based behavior as making use of, “previously-stored rules,” and relying on signs and indications from the environment to make perform actions. Rule-based behavior can be described as a “sequence of subroutines in a familiar work situation”, with examples including maneuvering an aircraft or vehicle. Rasmussen’s highest level of behavior is knowledge-based behavior, and which becomes engaged when the lower level processing stages of skill-based behavior are not available. Knowledge-based behavior relies upon of a mental model of the present situation, and “explicitly formulates” a course of action based on present information and the mental model. As a result, it takes the longest time to engage and is not ideal for active situations; when skill-based behavior and rule-based behavior or unavailable, reliance on knowledge-based behavior has led to aircraft accidents requiring rapidly timed decisions and actions. [34]

2.1.5.1 Performance Charts

According the Schmidt, a standard method of evaluating learning progress is through performance curves [37] Performance curves for a large group of people show the individual or average performance
rating versus practice trials. Typically, these curves follow the Law of Practice, which states that performance rapidly increases initially and slower later.

2.1.5.2 Acquisition and Retention

In order to alleviate temporal gains, and to demonstrate how learning is permanently retained over time, learning is typically evaluated in two stages: Acquisition and Retention. For Acquisition, individuals perform a set task, and are recorded and evaluated over an initial learning stage. After a significant time has passed, performance for the same tasks is re-evaluated to characterize retention. For example, a training aid that appears to increase performance over standard training procedures during acquisition may create an overdependence on the aid and the individual may show poor retention when tested several weeks later. [37]

2.1.6 Established Strategies for Learning

2.1.6.1 External vs. Internal Focus of Attention

Wulf defines internal focus of attention as a focus solely on the body's movement. For example, thinking about how to position one's hands in a pose. External focus, Wulf defines as focus on the environment. [43] Internal focus is typically useful only in the very beginning stages of learning a skill, to gain comfort with one's body and associated movement. External focus has been shown across a wide breadth of sports to produce a more skilled performance than use of internal focus.[42] In 2003, Wulf et. al., demonstrated a key experiment, two groups of individuals were instructed to stand on a "teeter totter" and either hold their hands level or hold a rod level; the task amounted to the same target result. However individuals who were instructed to "hold the rod level" significantly outperformed individuals who were instructed to hold their hands level and resulted in much better learning retention.[43]

2.1.6.2 Extrinsic vs. Intrinsic Motivation

Intrinsic motivation tends to lend itself towards more effective learning via capability for longer and more strenuous practice periods. According to Deci and Ryan, the degree of Intrinsic motivation is based on autonomy (control of one's destiny), competence (skill mastery), and relatedness. [35] Extrinsic motivation is driven by goals and external feedback. Boyce showed that setting specific goals rather than asking learners to "do your best" improved retention and performance.[8] Interestingly, augmented feedback can boost performance and retention as long as it is positive, even if it is untrue. [2]
2.1.6.3 Distributed vs. Blocked Practice

Distributed practice, that is separate blocks of shorter practice over multiple days has been shown to be significantly better for learning retention than blocked practice (all at once). [14] Notably, Baddeley and Longman conducted a study where postal workers were retrained in a keyboard-based task for 80 hours total. In this study, three groups were trained in blocks for either one to two hours per session with either one to two sessions per day. Groups with the least concentrated training periods, distributed over a long period of time, clearly exhibited the best performance and retention. [3]

2.2 Effects of State and Sensory Inputs on Performance

2.2.1 Arousal

Schmidt defines arousal as the level of excitement produced under stress, where conditional emotions such as stress and fear increase arousal. [37] Various authors have documented and proposed models governing the relationship between stress and focus of attention. It is generally agreed that the Inverted U Principle holds, where an individual's perceptual field becomes narrower under stress. More specifically, the inverted U Principle states that individuals performing skills have access to a large range of sensory and environmental cues, and that only some of these cues are relevant and useful. With higher arousal, attentional focus becomes directed to only the most relevant cues, up to a hyperarousal point, at which the performer is unable to usefully perceive any cues. With lower arousal, the opposite effect occurs. [16]

Another explanation for this phenomenon includes Attentional Control Theory, which says that individuals have a finite pool of mental resources that either becomes allotted to identifying cues for survival or processing the information to execute a plan. Increased levels of stress decrease useful attention space and increase attention to “potentially lifesaving cues” [17] By decreasing useful processing space, with too high stress all resources are devoted to looking out for critical cues, and nothing constructive can be done with them.

2.2.2 Role of Vision

According to Schmidt, vision plays an essential role in control of balance. [37] In particular, optical flow, that is pattern of movement picked up by the eyes of the environment moving relative to the person, has a prominent effect. [28] This information integrates with proprioception to have a significant influence on body movement with regards to balance and orientation. [20]. An especially keen exam-
ple of this was demonstrated by Lee and Aronson; they designed a room with movable walls placing a person at the center. By moving, rotating, and tilting the walls around the person, and without the floor changing, they were able to induce tilt and stumbling in the participants in the center.[27]. Their findings suggested that, alongside others, optical flow from cues in peripheral vision affect balance.

2.2.3 Role of External Sound

The role of sound effects on movement are much less well studied overall [37]. However a few prominent effects have been documented. The delayed playback of one’s speech or musical performance has been shown to affect timing of continued performance. Specifically the use of delayed audio from oneself has have some ability to aid with stuttering, effectively slowing speech [26]. Additionally, the McGurk effect demonstrates a tie between auditory and visual processing; playing specific sounds while being shown visuals of different mouth movements causes different types of sounds to be perceived. [37]

2.3 EXPLICIT AND IMPLICIT LEARNING

2.3.1 Explicit Learning and Declarative Knowledge

As defined by Liao and Masters, Explicit Learning is defined by deliberate use of problem solving strategies that make use of hypothesis testing to develop internal rules. [29] These internal rules are directly available to the conscious and are able to be articulated. [29] Explicit Learning is typically needed in the very early stages of learning to establish some conscious rules but has been shown to decrease ability to perform highly skilled or tasks requiring multiple attention foci.[25] Instead, expert ability is marked by a less deliberate, more automatic form of knowledge that is difficult to directly articulate - procedural knowledge. [25] Procedural knowledge is typically imbued using implicit learning, which entails learning without applying direct hypothesis testing.[29].

2.3.2 Implicit Learning and Procedural Knowledge

Contrary to Explicit Learning, Implicit Learning is characterized by learning without accruing more than the basic few rules about the "underlying structure" of the movement or skill being learned[29]. Implicit Learning was first demonstrated for motor skills by Masters in 1992 [31] who demonstrated that motor learning can take place without awareness of what is learned. As mentioned previously, implicit learning is synonymous with procedural knowledge.
2.4 METHODS FOR ACHIEVING HIGHER RATES OF LEARNING AND RETENTION

Liao et al. found that use of analogies enabled teaching of implicit knowledge, defining implicit knowledge as an inability to articulate clear declarative rules, and a robustness to performance drops when multiple tasks are going on at the same time, or the target skill environment is perturbed.

Similar to the findings Liao et al. found with analogies, Masters et al. found that use of minimally perceptible feedback "evokes implicit processes" and enables implicit learning with development of procedural knowledge. For example, when training newcomers to golf to putt accurately, newcomers more robustly maintained and built upon learning when exposed to only partial feedback; when hitting a ball, they were only able to see the approximate square in a 9x9 grid of where the ball landed vs. the precise location [30].

Taking another approach, Maxwell et al. developed a framework examining a large body of work examining explicit and implicit learning, concluding that working memory is saturated when attempting to learn declaratively (Working Memory Dependent) whereas in learning conditions that obscure, or make less deliberate feedback, (Working Memory Independent), working memory is not saturated, and instead lends itself towards higher rates of retention and forward knowledge transfer[32].

These theories together suggest that for robust learning retention and development of procedural knowledge, it is important not to provide explicit and precise feedback, but rather high level or partially obscured goals.

2.5 FORMS OF FEEDBACK

In order to convey these principles of learning for aid in teaching unfamiliar movements and skills, we sought to understand means and examples of providing augmented feedback. The following subsections survey the state of the art in augmented feedback for motor learning.

2.5.1 Forms of Augmented Feedback for Motor Learning

Sigrist et al. provides a comprehensive survey of present work in the domain of augmented feedback for motor learning [39]. Sigrist provides concise definitions for work in the field; Augmented Feedback is "information provided by a trainer or display", Motor Learning describes a lasting change of motor performance caused by training [39]. According to Sigrist, work in this field seeks to "enhance ... examples of complex motor (re-)learning by optimizing instruction and
2.5 Forms of Feedback

feedback. [39] Sigrist describes the multimodalities for effective feedback via figure 1.

![Figure 2: Modes of Providing Feedback. Solid=experimentally confirmed. Dashed=hypothesized Effectiveness=broadness. Sigrist et. al. 2013 Augmented visual, auditory, haptic, and multimodal feedback in motor learning; A review](image)

2.5.2 Demonstrated Auditory Displays for Augmented Motor Learning

Sigrist classifies auditory feedback into three categories; alarms: non-modified discrete sound to indicate exceeding a defined movement variable threshold; sonification: modulated sound to describe a movement variable via a mapping function; and sonification of movement error: modulated sound to describe the difference between a target trajectory and the present body trajectory.[39] While there have been numerous efforts to examine augmented visual feedback and audio feedback via alarms, there have been fewer instances of concurrent sonification or concurrent sonification of error to aid in motor learning. Within rehabilitation and sports, a prominent early design of sonification was demonstrated and evaluated positively for swimmers practicing their 100m crawl stroke; in 1988, Chollet et al., demonstrated retained improved performance after four days of training with their system that sonified body velocity using hydrodynamic pressure.[12] A series of sonified movements have been demonstrated for a variety of sports, from skiing, to carving, to gymnastics, however many of these systems have not been systematically evaluated. [39]. Additional drawbacks have been found in raw sonification, where advanced users can make use of the sound, and qualitatively indicate the system is useful, but novice users have little idea of how to use the system. [24]. Amongst the most complex systems with positive results, Chen et al., demonstrated a concurrent sonification system for controlling an arm in space for rehabilitative purposes that makes use
of distance to target and harmonic progression with strong results for improving speed, fluidity, and precision of motion. [10] Within gymnastics specifically, Baudry et al. successfully demonstrated a system that uses sonification of error to correct body positioning during gymnastics circles, with retained improvements over the control group for a training period of 2 weeks [5]. To be aware, Chiviacowsky et al. found that augmented auditory feedback for motor learning may inherently provide motivation independent of particular strategy efficacy that may improve outcomes regardless of feedback strategy.[11]

2.5.3 Spatial Auditory Targets

Grantham et al. performed significant work in understanding the ability of humans to perceive audio markers in motion, and at various relative placements spatially around the body. They found that people most easily distinguish distance, and are less able to distinguish speed of moving target markers.[22] Grantham et. al. also found that placement of audiomarkers in a surrounding landscape were easier to understand by horizontal and vertical varying placement relative to a body, but more difficult to understand when varying diagonally. [23]

2.5.4 Principles for Design of Auditory Displays

Flowers provides a comprehensive evaluation of strategies that have worked, not worked, and need to be explored for displaying auditory graphs. [19] Strategies that have worked with proven results include: correlating pitch with numerical values, exploiting the extremely high resolution of auditory perception for nuanced comprehension, use of loudness to indicate importance of information, using distinct timbres for perceptual grouping of auditory information streams, displaying information with time, and sequential display of information versus simultaneous.[19]

2.6 Wearable Sensing

Wearable sensing enables real-time tracking of physiological and movement signals unconstrained from medical or laboratory settings [33]. In particular for highly mobile applications, wearable sensors are advantageous over camera and ambient sensing environments, as they do not require cameras and restrict performers to set environments. [7]

Recently, wearable sensing has been enabled by the matured industry of micro-electro-mechanical sensors (MEMS) and wireless protocols. MEMS enable low power, small component sensors they may be integrated into clothing or worn devices, while wireless proto-
cols, such as IEEE 802.15.4 and Ultra-Wide-Band (UWB) radio enable non-tethered systems and tracking functionalities. In particular, MEMS have become commonly integrated into System-on-Chip designs, where sensing, computing, wireless transmission, and power management occur on a single package. Clever integration schemes and approaches have reduced large and complicated sensor packages to small sizes with effective results; for example time-of-flight range-finding distance SOC designs utilizing CMOS manufacturing techniques, distance sensors have been able to reach distances of up to 3 meters with refresh rates on the order of 50Hz within package sizes smaller than a dime. At the time of writing, STM Electronics produces design utilizing Single Photon Avalanche Diode arrays that reach approximately these specifications at a low cost. Advances in materials have enabled electronic-textile based systems, that integrate conductive threads, conductive elastomers, or fabric with unique properties to act as deformation or conductive elements of a sensor. The pervasiveness and power of mobile computing devices - smart phones - have additionally enabled more sophisticated computation, logging, and transmission of sensor information for local or cloud-based processing.

2.6.1 Sensor Placement and Integration

A number of sensing and placement strategies are used to measure physiological signals. Using micro-electro-mechanical sensors (MEMS), oftentimes body signal measurements can be measured using clever placement and choice of sensors. For example Corbishley et al. designed a system that measures respiratory rate by filtering signals from a microphone placed on the neck. Likewise, Asada et al., created a series of clever designs to measure pulse oximetry and blood pressure monitoring tackling both issues of wearable form factor and sensor placement for measurements. For example, in order to measure arterial hydrostatic pressure blood relative to the heart level, Asada et. al., integrated two offset MEMS accelerometers to determine height of a PPG sensor relative to the heart.

2.6.2 Flexible Sensor Schemes

One strategy for integration for wearable applications has been to create flexible sensors that enable body-conforming integration into tight clothes. Most commonly heart rate sensors via photoplethysmography (PPG) use this strategy, as sensors of higher sophistication often face motion artifacts.
2.6.3 IMU-based Schemes

A large number of wearable sensing schemes make use of Inertial Measurement Units (IMUs) which integrate multiple sensors together to provide acceleration and positioning information. These sensors typically incorporate MEMS accelerometers, gyroscopes, and magnetometers. IMU's have been applied to a very large set of motion tracking applications. For example, to track gait, Floor et al. demonstrated that the use of five IMUs attached to the thighs, shanks, and sacrum, is able to provide sufficient information to estimate a body's center of mass for rehabilitative applications. In the domain of sports event detection, Dorshsky et al. developed a framework to train a hidden Markov model on data from a worn IMU to enable limb-impact detection with projectiles such as soccer balls. [15]

2.7 RELEVANT LESSONS FOR THESIS GOALS

From previous work in this chapter we have observed a wide breadth of strategies for learning, providing feedback, and wearable sensing. Towards our goal of enabling individuals to learn unfamiliar motion, we take as strongest lessons from this work the importance of ingrain- ing procedural knowledge via implicit learning, creating an feedback system that makes use of variant of auditory sonification of error of a partially obscured goal, and to design a wearable system utilizing SOCs to enable unconstrained movement independent of specific environments.
3.1 Motivation for Requirements

As illustrated in 2, multiple methods of measuring, evaluating, and providing feedback for movement performance exist. We aim building upon findings that implicit learning can be achieved through use of partially obscured goals by defining physics-informed metrics and displaying the results using augmented feedback. Specifically, We hypothesize that simplified physics models may provide adequate performance tracking results to provide partially obscured feedback for implicit motor learning. To test this hypothesis, we have designed a wearable sensor device, simplified physics model, and an auditory feedback display pattern that uses a harmonic scale progression influenced by the work of [10] (see 2) to display obscured performance feedback to the user. We have chosen the case study of the front flip, in large part because of the interesting and challenging characteristics it poses; high-speed dynamic motion, an opportunity to simplify physics for a complex motion, and for the unique coaching and learning challenges it poses.

3.2 Core System Design Decisions

We created a set of design decisions that we hoped would get users familiar with and acquainted with the unique movement awareness space. Specifically, we aimed to enable learners to engage in implicit motor learning via feedback of obscured higher level goals. We aimed for our system to feed these high level goals using clever placement of simple sensors and an optimized simplified physics model, to create a system that requires minimal to no calibration or ambient sensing.

3.2.1 Auditory Feedback - Implicit Learning via Partially Obscured Feedback

As a motivating factor, and supported by work put forth in 2, we believe that feedback should provide high level information regarding the task but that does not provide explicit correction. Therefore, we explicitly decided not to sonify precise positions or angles of the limbs, but instead sonification of a physics-informed goal. We felt that sonification of a complex goal with harmonic feedback would create partially obscured feedback.
3.2.2 *Simplified Physics Model*

By targeting approximate objectives, we mostly eliminate the need for precise body tracking and position. For this reason we believe we can simplify and reduce many athletic physics tracking problems into very simple scenarios. This approach follows from the clever work of Shaltis et al., where sensory advances mostly follow from clever body placement and utilization of simpler sensor components.[38] We demonstrate one such scenario in the following chapter.

3.2.3 *Fully Wearable System*

Whereas many sensing systems make use of ambient sensing, we sought to decouple the practice and refinement of movement from a set environment. Hence we wanted to create a system that requires no external cameras or sensing equipment.
IMPLEMENTATION OF AN AUDITORY FEEDBACK SYSTEM FOR FRONT FLIPS

4.1 IMPLEMENTATION APPROACH

1. Understand and validate simplified physics for the front flip model
2. Design a wearable hardware sensor platform that enables sonification of some part of this model
3. Design impact detection and appropriate measuring algorithms to enable realistic execution of the model
4. Design a user interface that enables design and placement of the hardware sensor platform for a target motion

4.2 UNDERSTANDING THE PHYSICS OF FLIPPING

4.2.1 Simplified Modeling of the Flipping Problem

To begin, we wanted to understand if this motion could be simplified, specifically for the manner in which front flips are handled in gymnastics. Using some insight from gymnasts on the MIT gymnastics team, we learned that the body remains stiff, and mostly exerts a stiff downwards motion into the spring floor as a "punch" to initiate height, we modeled the body as a two-bar linkage with a spring-damper and motor at the middle hinge.

This system was modeled with generalized coordinates as found in Table 1.

| x | horizontal body distance from origin |
| y | vertical body distance from origin |
| θ₁ | relative angle between horizontal and bar 1 |
| θ₂ | relative angle between bar 1 and bar 2 |

Table 1: Generalized coordinates for simplified 2-D front flipping model
IMPLEMENTATION OF AN AUDITORY FEEDBACK SYSTEM FOR FRONT FLIPS

Figure 3: Generalized Coordinates for Front Flipping
performing maximum height flip?" and "What kind of flipping strategies arise from dominantly active torque vs. passive stiffness?"

Using insights from gymnastics experience, we came up with the following hypotheses:

- Passive stiffness has a greater influence than applied torque when performing high flips.
- High stiffness translates to low torque requirements for performing flips.

### 4.2.2 Nonlinear Optimization

We implemented the model in MATLAB, using the nonlinear solver fmincon with ode45 and a hybrid model to handle collision dynamics with the floor. We used an objective function of $\Sigma y_{cm}$ or maximum flip height to generate results. We included constraints of $\theta_1 = 2\pi$ radians at flip completion.

As inputs to this optimization, we incorporated the following variables.

<table>
<thead>
<tr>
<th>Initial Conditions</th>
<th>$[x_0, y_0, \theta_{1o}, \theta_{2o}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function</td>
<td>Maximise height of the flip, $y_{max}$</td>
</tr>
<tr>
<td>Optimized parameters</td>
<td>$t_f$, $t_{ctrl}$, $[T_1, T_2, T_3, T_4, T_5, T_6, T_7]$, $K_p$, $K_d$, $\theta_{2flight}$</td>
</tr>
</tbody>
</table>

Table 2: Optimization parameters. $t_f$ denotes time from start of simulation to end of simulation. $t_{ctrl}$ denotes final control time to interpolate torque profile values from simulation start to $t_f$. $T_1$ through $T_7$ denote torque values interpolated from start of simulation to $t_f$. $K_p$ denotes proportional spring gain for the virtual spring of the model. $K_d$ denotes the damping value for the model. $\theta_{2flight}$ denotes the angle between the top link and the bottom link, used to pick target degree of "tuckedness" during the flip.

From a visual standpoint, the results showed two characteristic type flips, 1) A gymnastics-type flip when optimizing for stiffness, and 2) a martial arts-type flip when optimizing for torque. This finding is the most critical, as for gymnastics type flips it provided a simplified physics model as a basis for characterizing a good or bad flip.

### 4.3 A SIMPLIFIED MODEL FOR OBSCURE PERFORMANCE FEEDBACK

#### 4.3.1 Guess: Flip Motion can be Approximated as Ballistic Motion

The kinematic equations for ballistic motion can be rearranged to depend only on initial velocity if initial velocity is given. As the results
suggest, flips are stiffness-dominated, we hypothesized that the flipping body could be approximated as a simple rigid body - even to the extent of being a point mass in ballistic motion. This guess would mean we need only three parameters to give a measure of parabolic success: initial velocity at takeoff, time at which initial velocity is recognized, and time at which a flipping individual reaches their peak height.

4.3.2 Model Verification: Simulation Time to Peak vs. Ballistic

From these modeling results, we compared direct ballistic motion with the stiffness-based model. After performing nonlinear optimization to achieve a flip trajectory, we compared the motion against ballistic motion. This trial was performed with units reduced by a factor of 10 to reduce ground constraint artifacts in simulation.

For this comparison, we denote the measured peak height of the flip trajectory as $h_{\text{peak, trajectory}} = 0.2281\text{ m}$. Given this simulation generated value for peak flip height, we back calculated to find initial velocity and time to peak using kinematic equations for ballistic motion.

Using Newton’s second law: conservation of energy:

$$\frac{1}{2}m v_0^2 = mgh_{\text{peak}}$$

where $v = \sqrt{2gh_{\text{peak}}}$, $g = 9.81\text{ m/s}^2$, and $h_{\text{peak}} = h_{\text{peak, trajectory}}$. We found $v_0 = 2.115\text{ m/s}$

Using kinematic equations to reach time to peak

$$h_{\text{peak}} = y_0 + v_0 t - \frac{1}{2}gt^2$$

we found $t_{\text{ballistic}} = 0.2152\text{ s}$ which compares against the flip simulation’s takeoff to peak time range difference of $t_{\text{flip, sim}} = 0.2555$. The difference in peak times is approximately 3.4 percent. Additionally, the initial velocity found from ballistic, 2.115 m/s compares to the measured simulation takeoff velocity of 2.1165, yielding an initial velocity error of 0.049 percent.

From these results, we deemed time to peak of ballistic motion to be a reasonable approximation of flip height from measured initial takeoff velocity.

4.3.3 Design Plan: Use Rotation to Dictate Peak Flip Height

By taking the initial vertical velocity at takeoff, we can calculate an ideal time to peak for well executed flip. Detecting a rotation event,
4.3 A SIMPLIFIED MODEL FOR OBSCURE PERFORMANCE FEEDBACK

Figure 4: Trajectory of the center of mass with the takeoff and the peak jump at times 0.3105 s and 0.5330 s, respectively. The time lapse is 0.2225 s.

we can find the difference between rotation event and peak height time as demonstrated by equations 3 and 4.

\[ v_y = v_o + a_y t \]  
\[ t_{\frac{1}{2}} = \frac{v_o}{g} \]  

We send the according time to peak from rotation event difference to be sonified as partial completion. More precisely, this motion completes a sonification pattern if the flip is executed with a peak rotation time equivalent to ballistic motion. The sonification pattern is incomplete if the rotation event occurs before peak time.

4.3.4 Sound Generation Strategy

Sound is generated as a progression of an F-chord of piano notes playing from takeoff until reaching the rotation event. At takeoff, the ideal time to peak is computed and the chord notes are interpolated from takeoff to the ideal peak of the trajectory. If the rotation occurs prematurely, for example before the peak time has been reached, the
chordal progression is cut off and pitched flat. This strategy enables two things. 1) users can simply tell that more notes heard means better performance, and 2) the performance is described by a the difficult-to-directly-conceptualize ballistic trajectory. Achieving a more ideal ballistic trajectory yields positive sounding results, but with some ambiguity for direct mapping in order to partially obscure results in hopes of encouraging implicit learning.

4.4 WEARABLE HARDWARE SYSTEM

Figure 5: AUFLIP Ankle-worn Sensor, Ankle Band, and Battery
4.4.1 Designed Specifications

1. Wearable only, no external camera required.
2. Responsive within 30ms for takeoff detection.
3. External storage for logging data.
4. Wireless transmission to enable nontethered placement on the body.

4.4.2 Base Platform and Chosen Sensors

As a wireless wearable sensor platform, we based our design on the MAX32630FTHR microcontroller platform. Multiple streams of data were read and processed using threading on top of the MBED Real Time Operating System. The code running on this device can be found here.

This sensor platform was chosen for fine control over its sensor and storage capabilities - it contains a BMI160 IMU, 3 I2C lanes, an ARM M4 Cortex with floating point support clocked at 96kHz, an SD Card Reader, and programmable user interface buttons and LEDs.

It additionally runs the MBED real time operating system, supporting threading for uninterrupted and rapid streaming of information, important for the chosen high speed dynamic motion.

We designed a custom PCB that enabled secure integration of the VL53L1 time-of-flight distance sensor as well as holes for strapping it to the ankle.

Originally, we implemented a Kalman Filter for angles in the sagittal plane determined from IMU readings, sound capture via microphone, and distance sensing. After initial testing, we found that the microphone and IMU readings were overly noisy during the dynamic motion of the front flip, while the distance sensor readings appeared intact. As a result, our implement the sole means of capturing relevant motion features for developing auditory feedback.

Bluetooth Bridge Implementation  Bluetooth was designed as a custom GATT service with two autonotifying characteristics on a GATT stack. Each characteristic stored a 16 bit unsigned integer. The first characteristic updated and notified its value upon detecting a velocity rise event - where the initial takeoff for a flip took place.

The second characteristic updated its characteristic upon rotation event detection.

Using a combination of threading and interrupts, we confirmed that the delay in interrupt execution was no longer than 40ms.

These bluetooth characteristics are connected to an iPhone 8 via BLE, and processed by a custom iOS application. The application computes takeoff velocity and time to rotation from these readings.
4.4.3 Final Sensor Scheme: Distance Sensing with Smoothing

In the final design, the system exclusively made use of distance sensor measurements from the onboard STM VL5LoX time-of-flight ranging sensor. Readings were performed at approximately 33 Hz. Smoothing was performed using a box filter over \( n = 20 \) readings.

**Data Logging for Development** To design takeoff velocity measurement and rotation event detection, we developed a scheme to record sensor data. Per data recording trial, sensor values were loaded into a circular buffer array, and at trial end loaded onto a FAT formatted SD card as text files. To match video with recording data, we created tablet-based app that syncs video recording upon button press on the wearable sensor device for logging. The camera component of this app integrates the NextLevel Camera pod from the package managing service CocoaPods.

4.4.4 Takeoff Detection and Translation of Sensor Information into Physics Model

The system principally uses a threshold to identify the takeoff event, and upon detecting the event measures twenty datapoints, averaging and subtracting the last and first five to achieve an initial velocity. The threshold is set relative to the starting position of the sensor; after securing it to the ankle, when turned on, the sensor places a threshold of 10 cm relative to its starting position. Users engage in a three step hurdle pattern to engage the takeoff event - see 6 and 22.

When the initial velocity is registered, it is sent to the iOS app via bluetooth. The initial velocity is fed into the ballistic model 3, and time to peak is computed.

4.4.5 Use

The system has two states; listening for activation, and no action. To enter the listening-for-activation state, the user pushes a button near the top of the AUFLIP device (see 8). The device light turns red when in "armed" preparation mode. After executing the flip and hearing the auditory feedback, the device is reset by pushing the button again twice. The first time pressed turns the device light blue and enables free walking without auditory feedback. The second time pressed reactsives "armed" mode in preparation for the next three-step hurdle pattern.

4.5 Sonification iOS App

To sonify information we built a custom app **App Architecture** The app is composed of 4 classes. see 9 Class "Pegasus" handles direct
Figure 6: Strategy for picking up initial takeoff velocity. In order to pick up takeoff, the system uses a threshold distance calibrated from sensor turn-on and looks for values rising above this step. Upon the third step, 20 steps are stored in a buffer, and the first and last 5 are averaged with respective timesteps to determine takeoff velocity.

Figure 7: Using the AUFLIP Feedback System: activation pattern for triggering physics model uses demonstrated three-step takeoff technique
IMPLEMENTATION OF AN AUDITORY FEEDBACK SYSTEM FOR FRONT FLIPS

Figure 8: Using AUFLIP for evaluation and feedback. Two modes: blue = passive and red = looking for takeoff pattern and preparing to generate feedback.

"Pegasus" class and generates results from the physics model. Class "Generator" is used by the computer to generate appropriate sounds.

External Hardware

Figure 9: AUFLIP App Architecture
4.6 AUTOMATED SENSOR PLACEMENT

We designed a graphic user interface to run the simplified physics simulation, given a performance objective and body dimensions to determine sensor placement. This simulation environment simulated the AUFLIP sensor package abilities; distance sensing at 40Hz and approximate impact detection using a "simulated microphone."

![Diagram](image.png)

**Figure 10: Overall Sensor Placement**

Automated placement works by first running a nonlinear simulation of the two-linkage model. After running the simulation and discerning trajectories, the algorithm searches through angle and placements along the linkages.

4.7 USER INTERFACE FOR ENABLE CUSTOMIZED FEEDBACK PROFILES FOR VARIOUS BODY DIMENSIONS

Lastly, we implemented a graphical user interface to enable users to input various body dimensions and objective functions. The goal of this GUI is customization and enabling proper placement for a range of physics and ability. For example here, the flip simulation is optimized and run with the goal of placing the sensor position and angle such that it maximizes the time the distance sensor views the ground.
IMPLEMENTATION OF AN AUDITORY FEEDBACK SYSTEM FOR FRONT FLIPS

Figure 11: Data for angle and position across body

Figure 12: The Sensor GUI takes the parameters of the person and provides an ideal location and orientation based on the chosen objective function. Two cases are shown here: A) The Sensor Detection function gives back the location that has the best percent detection of the trajectory. B) The Maximum Height function that finds the farthest distance the sensor can be placed from the ground. The GUI creates a diagram showing the placement of the sensor on the specified person.
USER STUDY: TRAINING AND USE OF AUFLIP SYSTEM

This study was approved by the MIT Council of Human Subjects Testing - NO. 1712179307. In order to obscure gender of participants, we will refer to participants in this study as "they" rather than "he" or "she."

5.0.1 Questions and Hypotheses

Entering this study, we had two main questions.

1. Can auditory feedback of an obscure goal encourage implicit motor learning in teaching flips alongside gymnastics coaching?

2. What kinds of learning are dominant in this training process?

We expected to see that with the AUFLIP feedback system, participant articulated mental models of declarative rules governing the front flip remain relatively constant, and that the observed performance in executing front flips increases.

As an initial hypothesis for our second question, we expect that coaches will lower working memory requirements of participants as they are viewed as someone who knows the process and will handle the rules. As additional commentary, we documented participants' and coaches' thought process through freeform interviews.

5.1 METHODS

5.1.1 Participants

Nine participants were recruited via email, poster, and word of mouth from the MIT campus. Of those nine, six participated in this study. All participants were MIT students (age range: 21-28, mean: 24.8, std: 2.67) who had never performed front flips before. Before engaging in the study, participants completed a consent form in compliance with COUHES protocol NO. 1712179307. As an initial pre-screening, participants were required to pass a baseline safety training, meaning that within one hour of safety training with a coach, they were able to perform a forward dive roll consistently and were judged by the coach to be safe. After passing screening, participants were trained by a professional coach in basic safety techniques up to performing a basic front flip, and randomly assigned whether or not they would be performing front flips with the AUFLIP feedback device.
5.1.2 Apparatus Setup

5.1.2.1 Gymnastics Facility

The study took place in the gymnastics facility of the Dupont Gymnasium on the MIT Campus.

For every participant, individual instruction was provided by a United States of America Gymnastics (USAG) certified instructors; one researcher and one coach. Instructors were paid a competitive rate as compensation for their work.

![MIT Dupont Gymnasium Gymnastics Facility](image)

The following training drill stations were setup and used across this study:

5.1.2.2 Training Exercises

See 8.3

5.1.3 Data Collection

Before the participating in the study, participants filled out a screening questionnaire detailing their athletic background, confidence in their ability to perform front flips, and their availability.
5.1 METHODS

5.1.3.1 Pre Trial
Upon entering the gymnastics facility participants were asked a series of pre-trial questions to evaluate sleep, stress level, and their pre-trial mental model understanding of the flip movement.

5.1.3.2 During Trial
During each session, participants were recorded by video and audio. These recordings were analyzed by reviewers to determine flip or dive roll performance based on a rubric and the judgement of experienced gymnast reviewers.

5.1.3.3 Post Trial
After each session, participants were asked a series of questions by questionnaire (see Appendix 8.1). They were also asked questions in informal discussion about their experience. Questionnaire responses for flip descriptions were scored by three reviewers with greater than ten years of gymnastics experience.

5.1.4 Training and Evaluation Procedures
Per participant, the study was broken into up to four 1-hour sessions. During each session, participants were asked questions about their state and experience prior to training, and after training. The sections Phase I, Phase II, and Phase III, detail the training and evaluation procedures.

See 18 for mental model rubric, and 19 for flip performance evaluation rubric.

5.1.4.1 Phase I Safety Training
To test baseline ability, participants were initially brought in and taught basic falling techniques, a forward roll progression, and with time permitting, a dive roll. If participants could not safely or consistently perform the forward roll or dive roll, they were dismissed from the study with compensation.

5.1.4.2 Phase II Basic Flip Training
Each user that passed the safety baseline was brought in for three additional one-hour sessions. If safety training was completed within the first hour, participants were taught additional basic roll and dive roll skills. Each user was given individual training in a fully equipped gymnastics facility, incorporating a gradual progression through use of spoken feedback, tactile feedback (spotting skills for confidence/safety), and visual feedback via demonstration of technique. The use of these
techniques was at the discretion of the assisting coaches. Training participants to safely do a flip took place over the first two 1-hour sessions. During the period, dive-rolls and progress towards flips were evaluated using reviews of the last seven minutes of footage recorded per session. The third and fourth sessions were used for evaluation if participants were able to perform a basic front flip on the "Tumble-trak," a trampoline-like surface, into a "Resimat," a 48" thick polyurethane safety mat, by the end of session 2. Many participants however were not ready for front flips until the fourth session, meaning that most flip evaluation data was collected in session 4.

5.1.4.3 Phase III Flip Evaluation and Refinement

After demonstrating a consistent ability to perform front flips, participants were evaluated for flip quality and flip height. Flip quality is a subjective metric defined by the researcher and coach, taking into account appearance of control and parabolic motion. Flip height was is a measurement of the height reached by the body's center of rotation. These qualities were determined from recorded video of the flip trials.

Free Flip: Eval Environment I For earlier participant evaluation trials, participants flipped from the Tumbletrak freely onto a low Resimat. This however did not work for all participants, as some participants still experienced difficulty landing. For later participants who experienced difficulty landing, we incorporated a different evaluation technique in their final trial tests - flipping or high dive-rolling onto a padded elevated surface.

During this evaluation, coaches only gave feedback once every five turns. Participants were told they could view themselves on video if requested.

See Appendix 8.2.1 for images.

Flip onto Elevated Surface: Eval Environment II For later participant evaluation trials, participants flipped from the Tumbletrak freely onto a high Resimat. The requirements were loosened somewhat so that participants were not significantly restricted if they found difficulty landing. This evaluation still enabled participants to focus on the first part of the movement, striving towards a strong parabolic motion and required the same base flip level as the previous method.

During this evaluation, coaches only gave feedback once every five turns. Participants were told they could view themselves on video if requested.

Participants wearing the AUFLIP auditory feedback system trained in this environment exclusively.

See Appendix 8.2.2 for images.
5.2 RESULTS

Because this study only reviewed six participants, we detail each participant's training and evaluation scores individually.

![Average Evaluated Flip Performance per Session](image)

Figure 14: Average Skill Performance Scores. Rated according to rubric by one USAG approved instructor. Session 1 is a basic training session. Sessions 2 through 4 are split into A, B depending on participant performance. A indicates that a user was able to perform evaluation skills throughout an entire session. B indicates that a user engaged in training drills during the first half of the session and performed evaluation skills throughout the second half of the session only. Of note, participant 5 did not perform flips until session 3. Rated performance captured the last 7 minutes of each session. Triangle indicates that participant trained with augmented feedback. Square indicates that participant was a control and did not train with augmented feedback. Error bars not shown for clarity; per participant, refer to the appendix to view error bars per trial 23,25,27,29,31,33, for participants 1 through 6 respectively.

5.2.1 Participant 1

Participant 1 recreationally engaged in sports for baseline fitness. The participant was in their late twenties. They did not comment on their feelings towards learning a front flip.

Participant 1 participated in 2 out of 4 sessions.

Participant 1 learned how to dive roll by the end of session 1 - completing Phase I and entering Phase II. By the end of session 2 the
Figure 15: Average Mental Model Scores. Rated according to rubric by three experienced gymnast reviewers (each greater than eight years performing front flips). Session 1 is a basic training session. Sessions 2 through 4 are split into A, B depending on participant performance. A indicates that a user was able to perform evaluation skills throughout an entire session. B indicates that a user engaged in training drills during the first half of the session and performed evaluation skills throughout the second half of the session only. Triangle indicates that participant trained with augmented feedback. Square indicates that participant was a control and did not train with augmented feedback.

Figure 16: Average Performance Scores vs. Mental Model Scores. Triangle indicates that participant trained with augmented feedback. Square indicates that participant was a control and did not train with augmented feedback.
5.2 RESULTS

<table>
<thead>
<tr>
<th>Sleep</th>
<th>Control</th>
<th>Fear</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.42</td>
<td>4.05</td>
<td>4.10</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.768</td>
<td>0.621</td>
<td>0.875</td>
</tr>
</tbody>
</table>

Table 3: Reported Average Post-Trial States

<table>
<thead>
<tr>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.00</td>
<td>4.70</td>
<td>N/A</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.77</td>
<td>2.00</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4: Participant 1 Average Flip Performance per Session. Score is from 1-8. Performance score was rated by USAG approved instructor using rubric 19

<table>
<thead>
<tr>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.00</td>
<td>3.00</td>
<td>N/A</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.00</td>
<td>1.00</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 5: Participant 1 Mental Model Score per Session. Score is from 1-4. Performance score was rated by 3 gymnasts with each greater than 8 years experience using rubric 18

Participant was able to perform a front flip - Phase III. Participant was a control, and did not use the auditory feedback system.

A detailed account of Participant 1’s performance, training, and comments across each session can be found in the Appendix 8.7.1.

5.2.2 Participant 2

Participant 2 came from a background of heavy fitness training. They were in their late twenties and felt confident in their ability to learn a front flip. They attended all four sessions. They slept an average of seven hours before trials.

<table>
<thead>
<tr>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.60</td>
<td>4.60</td>
<td>6.50</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.54</td>
<td>0.94</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 6: Participant 2 Average Flip Performance per Session

Participant 2 engaged in 4 out of 4 trials.

Participant 2 learned how to dive roll by the end of session 1, completing Phase I and entering Phase II. By the end of session 2 the participant was able to perform a front flip, entering Phase III. Participant 2 used the auditory feedback system for the second half of session 3, and the entirety of session 4.
Table 7: Participant 2 Mental Model Score per Session. Score is from 1-4. Performance score was rated by 3 gymnasts with each greater than 8 years experience using rubric 18.

A detailed account of Participant 2's performance, training, and comments across each session can be found in the Appendix 8.7.2.3.

5.2.3 Participant 3

Participant 3 came from a generally athletic background, with a history of sports participation in endurance-based sports. They were in their early twenties. They did not comment on their feelings towards their learning a front flip.

Table 8: Participant 3 Average Flip Performance per Session

Table 9: Participant 3 Mental Model Score per Session. Score is from 1-4. Performance score was rated by 3 gymnasts with each greater than 8 years experience using rubric 18.

Participant 3 engaged in 4 out of 4 trials. Participant 3 learned how to dive roll by the end of session 1, completing Phase I and entering Phase II. By the end of session 2 the participant was able to perform a front flip, entering Phase III. Participant 3 performed front flips during the second half of session 3, and the entirety of session 4. Participant 3 was a control, and did not use the auditory feedback system.

A detailed account of Participant 3's performance, training, and comments across each session can be found in the Appendix 8.7.3.
5.2.4 Participant 4

Participant 4 came from a generally athletic background, with a history of sports participation in endurance-based sports and present activity on club sports teams. They were in their early twenties. Participant 4 was motivated and confident about their ability to learn a front flip.

<table>
<thead>
<tr>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.16</td>
<td>5.00</td>
<td>4.50</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.75</td>
<td>1.69</td>
<td>2.38</td>
</tr>
</tbody>
</table>

Table 10: Participant 4 Average Flip Performance per Session

<table>
<thead>
<tr>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.00</td>
<td>4.00</td>
<td>3.66</td>
</tr>
<tr>
<td>Std Dev</td>
<td>1.00</td>
<td>0.00</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Table 11: Participant 4 Mental Model Score per Session. Score is from 1-4. Performance score was rated by 3 gymnasts with each greater than 8 years experience using rubric 18.

Participant 4 participated in 3 out of 4 trials.

Participant 4 learned how to dive roll by the end of session 1, completing Phase I and entering Phase II. By the end of session 2 the participant was able to perform a front flip, entering Phase III. Participant 4 performed front flips during the second half of session 3. Participant 4 used the auditory feedback system.

A detailed account of Participant 4’s performance, training, and comments across each session can be found in the Appendix 8.7.4.

5.2.5 Participant 5

Participant 5 recreationally engaged in sports for baseline fitness. They were excited about the idea of learning a front flip. They were in the mid twenties.

<table>
<thead>
<tr>
<th>Session 1</th>
<th>Session 2</th>
<th>Session 3</th>
<th>Session 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.66</td>
<td>2.50</td>
<td>5.00</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.77</td>
<td>0.83</td>
<td>1.69</td>
</tr>
</tbody>
</table>

Table 12: Participant 5 Average Flip Performance per Session

Participant 5 participated in 4 out of 4 trials.

Participant 5 learned how to dive roll by the end of session 1, completing Phase I and entering Phase II. By the end of session 3 the
Table 13: Participant 5 Mental Model Score per Session. Score is from 1-4. Performance score was rated by 3 gymnasts with each greater than 8 years experience using rubric 18.

participant was able to perform a front flip, entering Phase III. Participant 5 performed front flips during the second half of session 4. Participant 5 used the auditory feedback system.

A detailed account of Participant 5’s performance, training, and comments across each session can be found in the Appendix 8.7.5.

5.2.6 Participant 6

Participant 6 was in their late twenties and came from a martial arts background. They did not comment on their feelings of their ability towards learning a front flip.

Table 14: Participant 6 Average Flip Performance per Session

Table 15: Participant 6 Mental Model Score per Session. Score is from 1-4. Performance score was rated by 3 gymnasts with each greater than 8 years experience using rubric 18.

Participant 6 participated in 3 out of 4 trials, however, data was lost for trial 1, so only 2 out of 4 trials are included here.

Participant 6 learned how to dive roll by the end of session 1, completing Phase I and entering Phase II. By the end of session 2 the participant was able to perform a front flip, entering Phase III. Participant 6 performed front flips during the second half of session 2, and all of session 3. Participant 6 was a control and did not use the auditory feedback system.

A detailed account of Participant 6’s performance, training, and comments across each session can be found in the Appendix 8.7.6.
5.3 DISCUSSION

5.3.1 Complexity of Protocol

In establishing a protocol to evaluate the role of obscured auditory feedback into training for the dynamic motion of the front flip, we encountered a series of challenges that were reactively addressed during the study.

The initial screening of confident falling, forward rolling, and dive rolling within the first session appeared to be effective in filtering for a baseline ability to perform the physical action. Recruitment appeared to filter for highly motivated and curious individuals who wanted to try something new. All participants were able to, by the end of attended sessions, perform front flips.

During training, coaches mostly performed their usual training routines. Coaches were able to get most participants up to level of doing front flips within two sessions. Ability and styles differed slightly as expected amongst the participants. Of note, Participant 5 and the reviewed mental model scores showed unique internalizing of rules; in contrast to participants 2 and 3 who showed a decrease of explicit understanding but increase of performance in the final evaluation session, participant 5 appeared to more slowly improve performance and understanding together towards the final session.

Interestingly, most participants had some difficulty and expressed most fear with regards to landing the front flip. This observation led us to use a flip drill for final evaluations in session four; we had participants flip onto a large mat and bypass the landing timing to reduce fear while still enabling practice of the main motion.

Some of greatest challenges we experienced with our present protocol were

1. The ability to have participants come in for all sessions - three out of six participants did not participate in all four sessions.

2. Varying progression levels with limited sessions- participants progressed at slightly different rates, meaning that by session four, participants had just reached a point where they could effectively perform flips for refinement and evaluation. A larger number of sessions are recommended. The augmented auditory feedback device was only worn by participants at most 1.5 out of 4 sessions. Furthermore, due to the limited time we had with participants, our protocol did not include a retention study, which is critical to fully understand whether learning is implicit or explicit.

3. Variance in coaching styles from day to day - we had three coaches with slightly different styles teach the participants. The same coach often used different styles with participants with
some randomness; coaches often made use of the present configuration of the gym’s equipment to design drills which depended on previous attendees of the gym.

Fortunately, in use, the augmented auditory system was relatively consistent in executing properly, and while we received some feedback that the three step pattern used for auditory activation felt limiting, it appeared to be learned and consistently executed within a single session of teaching.

For future protocols for integration with a wearable auditory feedback device, we believe that the screening procedure and use of professional coaches to teach a baseline front flip were effective. The protocol needs to more effectively retain and maintain a larger pool of participants, and the protocol should at least reach six sessions total. For flip evaluation, the protocol should eliminate the landing component using the large Resimat landing pad shown in 8.2.2. The protocol should also include an additional two sessions a few weeks after the completion of the initial six sessions to better understand retention for better determination of implicit learning from auditory feedback.

5.3.2 Observed Progression and Interpretation of Motor Learning

During training, we observed the coaches make use of a variety of coaching principles outlined in 2. Coaches frequently created points of external reference, for example, asking participants to “watch a point on the wall” as they rise towards the flip. These external references follow findings that attention directed externally tended to result in enhanced performance and knowledge transfer over focusing solely on the body’s movement. The strategy also appeared to tie into building more robust understanding of the skill via random training; participants were moved through similar drills on various different material and springy surfaces throughout the gym.

Using these training techniques, we observed a progression that reasonably appeared to fit with Bernstein’s and Fitt’s Stages of Motor Learning. Participants began very stiff and trying to maintain complete control. It was especially observed that participants were reluctant to place their bodies completely in the air during the dive roll and flip maneuver. After gaining some base confidence and familiarity with the feeling of being in the air, they appeared to use more passive dynamics, as required by the target skill, to develop the flip itself. These actions appear to follow Bernstein’s Motor Learning Stages I and II in observed performance, as well as Fitt’s Motor Learning Stages I and II in observed mental model progression. The relationship between performance and mental model, generalized across participants that completed all four sessions appeared to suggest implicit learning, with a decrease in apparent explicit understanding of flipping rules but an increase in performance. For this particular ob-
5.3 DISCUSSION

These observations occurred when coaches engaged in fading; removal of feedback as participants became acquainted with the basic skill.

Lastly, coach training combined with use of the AUFLIP auditory feedback device appeared to contribute towards Schema learning, helping participants develop an overall set of feelings and intuitions for common cause-and-effect actions around the skill. By the fourth session, participants 2 and 3 stated that they could feel at the start of the skill whether the result would turn out well or not. Participant 2, with the device commented how it matched and bolstered their internal feelings regarding their performance via sound. Participant 3 on the other hand, commented that while they developed an intuition around the result of the flip, they also developed a hesitation - perhaps in trusting themselves. They claimed that for these reasons they tended to balk and give up with some frequency. This may have contributed towards their overall higher variance and lower final average in performance (see 29).

5.3.3 Explicit Learning vs. Implicit Learning? Examining the Matched Pair of Participant 2 and Participant 3

While all three participants had some interesting commentary around their experience with the feedback system, Participant 2 used the system most extensively, and their performance exhibited interesting qualities. Participant 3 provides the most direct comparison to Participant 2's performance as a control; both Participant 2 and Participant 3 moved through training at about the same rate, achieving controlled front flips before the third session, and both performed two sessions worth of front flips. For these reasons, this discussion will focus on the matched pairs of feedback-wearing Participant 2 and control Participant 3.

First, for Participant 2, flip performance increased across all trials, maintaining a near even spread of data close to +/- 1 rating point. Participant 2 exhibited the highest flip quality amongst all participants with a relatively tight spread in ratings. For later trials, most other participants "bailed" on their target motion a few times while Participant 2 did not. However, this could also be attributed to Participant 2 as having a high aptitude for learning motor movements. Further trials would need to be conducted with participants using the feedback system to discern conclusive evidence towards this possible finding. Participant 3’s performance rose through session 3, before decreasing slightly in session 4, in large part due to variability of performance. While Participant 3 was able to achieve strong flips in the 7 out of 8 point range, participant 3 also bailed on a few attempts and exhibited overall inconsistency in height, form, and apparent control. Participant 3 mentioned that while initiating the flip, they felt that they
could feel when they were "getting enough height to flip – sometimes [they] would feel that no, the jump would be a bad one," giving up right before flipping, or partially committing to the flip.

Second, the rated mental model, as evaluated by reviewer's comprehension of the participant's front flip description, increased with variance up through session 3, but decreased dramatically with full consensus amongst reviewers after session 4, from 3.33 with a STD of 0.4, to 2 with a STD of 0. Interestingly, the themes of participant 2's commentary also appeared to change. In session 3, participant 2 made a series of comments on the feedback provided by the device, insisting that "It [would] be better if the feedback is more clear," "[I know] the movement involves two parts, jump and roll, ... the feedback [did] not specify ... which part I did well and which I didn't." In session 4, they remarked that, "the sound is consistent with my own feeling ... three sounds, felt delayed rotation [...] felt good." Yet, at the same time, they felt that "when [they] did not do well, they did not know what [they] did wrong." Despite the obscurity of the signal, they also felt that "With the help of the sensor, I realized that jumping higher is more important and a little bit forward is enough," yet the sensor never explicitly gave them this information. In addition, feeling that the sensor helped them achieve a high jump, when describing their best and worse experiences of the day, they described their best as "Jump[ing] higher," and their worst as "Not knowing how to jump higher." This dichotomy appears similar to observed characteristics of implicit learning, where athletes can achieve a desired performance, but cannot articulate how they managed to achieve that performance. It might also be the case, that by trusting the feedback device as an agent that "knows" good and bad performance, participant 2 reduces loading of their working memory, as they felt positive performance and positive feedback line up. On the flipside of this idea, however, when the feedback device provided false negative information - as in it failed to generate sound on one occasion, participant 2 rationalized the result as their own failure to perform a good front flip, "I didn't jump high enough, no sound," as if the device was a coaching entity providing trusted, absolute judgement.

While Participant 3 overall also improved from study start, Participant 3's performance was considerably more variable, increasing towards the fourth session, with an average performance score of 5.33 out of 8, and standard deviation of about 2 points. Much of the variability exhibited by Participant 3 came from failed attempts; Participant 3 appeared much less sure of and would occasionally bail on an attempt. Participant 3 commented that they felt, "inconsistent," But felt like they could tell at flip takeoff, "whether my flip would turn out well or not." As with Participant 2, Participant 3 was also observed to have a rise in mental model understanding up until the last session. Participant 3 was also observed to be trying to figure out rules
5.4 LIMITATIONS

With a sample size of six participants, we do not have enough evidence to conclusively suggest findings. However, the information from this study anecdotally brings up some interesting insights.

- The sample size for this study is too small for statistical significance. While this study provides some potentially interesting potential findings, it cannot be taken as conclusive evidence itself.

- As the study progressed, the final evaluation setting was modified; this limited the number of comparable control and experimental trials.

- Out of 6 initial participants, only 3 managed to complete all four sessions.

- While skill level was kept at a relatively increasing rate amongst participants, we did not capture enough trials over enough times to effectively show learning transfer or retention.

In light of these limitations, this study yields only preliminary results but provides a basis for establishing a stronger method of training and evaluation.
6.1 GENERALIZED FLOW

Figure 17: General User Flow

In the previous chapters, we demonstrated a process for designing a wearable auditory feedback system with a partially obscure performance goal for the front flip movement. The system used some expert knowledge and optimization techniques to verify a simplified physics model, and linked it to an auditory feedback display pattern that provided obscured performance feedback to the user. Towards applications of this strategy to a wider breadth of movements in the future, we outline in this chapter an interaction loop for how users may tailor feedback to train particular motions and train for various different motion types. We define these motion types as "motion primitives."
6.2 SELECTING MOTION TYPES - DEFINING MOTION PRIMITIVES

From surveyed motion types, we classified movements into four main types where we could define feedback methodologies and constraints.

6.2.1 Ballistic Type Motions

Motions that require launching off of the ground. Examples are flips and jumps. These often require a rapid, well timed exertion, that is not easily modifiable after output. These motions are typically preplanned and required to play 100ms before timing takes place in order to properly time end results.

6.2.2 Repeated Locomotive

These kinds of motions include walking gaits, crawling, and various forms of locomotive dance. These movements often tie into the body’s rhythmic encoding of movement.

6.2.3 Static Balance

Maintaining static position, from static strength positions in gymnastics, to balance poses found in yoga, to sitting with good posture in a chair.

6.2.4 Hitting a Projectile

These movements tap into hand-eye coordination. Like ballistic motion, these motions often require preplanning. For the projectile case, towards this generalized system, we implemented a simplified model of tennis ball hitting as a double pendulum. The model has not been completed in simulation at the time of writing, but we believe that these various movement types can be similarly encoded and optimized for feedback.

6.3 SELECTING A HIGH LEVEL PERFORMANCE OBJECTIVE

6.3.1 Explicit or Implicit Goal

Once selecting a movement type, a user would select a performance objective. For a general system, the goals would describe qualities of the motion type in layman terms, and use the underlying physics of the description to inform audio feedback. As with coaching techniques, these targets could be explicit or implicit depending on the goal of the user; explicit for very specific correct condition of a sim-
6.4 OPTIMIZING SENSOR PLACEMENT AND FEEDBACK PROFILE

Potential Energy = Kinetic Energy
\[
\frac{1}{2} k (\Delta \theta)^2 = \frac{1}{2} m v_{\text{max}}^2
\]

Figure 18: Diagram of the double pendulum model for a racquet swing parameters necessary in the transfer of energy equation. \(\theta\) represents the angle from initial rest position, \(L_1\) is the length of the arm, and \(L_2\) is the length of the racquet.

plified portion of the motion or implicit for bigger picture refinement. Explicit goals would directly sonify single attributes of a skill. "Did I raise my hand higher?" "Did I run faster?" Implicit goals provide an obscure metric that provides feedback on a fundamentally important aspect of the skill, but is sufficiently obscure to reason about as to prevent direct declarative reasoning. These goals could be categorized as "define a particular part of a skill" vs. encourage retention towards a high front flip. Using motion type and a performance objective, the system would perform an optimization to determine placement of the sensor, sensors used from the wearable platform, and generate a feedback profile, as illustrated for the flipping case in 4.

6.4 OPTIMIZING SENSOR PLACEMENT AND FEEDBACK PROFILE

6.4.1 Automated Sensor Placement

Using extensions of the technique described in 4, the system would use the input movement type in conjunction with a high level performance objective to yield an auditory feedback profile. As performed for the flipping case, the motion primitive model of a skill would be optimized for a specific goal set, and the optimizer would find the optimum location on the model to enable best sonification of the end goal, and output the location and angle of placement of the sensor for the learner to place it on their body.
6.4.2 Feedback: Creating Auditory Feedback Specific to a Person

We envision that the system would output sound profiles that convey appropriate physics characteristics that inform the input target characteristic. Based on the flip case, we initially designed this generated sound as spaced notes of a chord. The notes would be spread out across the output metric, and would enable learners, as they do with AUFLIP, to engage with a further complete or less complete chord depending on their performance.

While scoping this next step, we sought to systematically determine how to create auditory feedback that closely relates to an individual person’s sense of movement. To do this, we looked towards Visual-Audio Congruence to suggest a notion of Movement-Audio Congruence.

6.5 Motivating a Notion of "Movement-Audio Congruence" by Visual-Audio Congruence

Over the course of this AUFLIP work, a common and strong question that has held throughout is - "What makes a good sound mapping for feedback?" Various qualities of sounds have been described, but in conducting this work we have found little that explicitly describes choice of sound for specific purpose of analogy. We hope to find, and believe that there may exist a strong mapping between audio and movement along the lines of Visual-Audio Congruence.

6.5.1 Creating Sound Analogies: a Hypothesis

From the work discussed in 2, implicit learning can be taught by analogy. Usually these analogies are verbalized. X experience is like Y experience. However, we believe the following may hold for sound - someone who hears the sound of a familiar movement-making machine or object may create rapid association with forms or types of movement if told the sound is associated with a specific body part.

As an initial step towards systematic sound generation, we evaluated this hypothesis in a preliminary study. For this preliminary study, we refer to participants by "they" rather than "he" or "she" to conceal gender.

6.5.2 Preliminary Study for Sound Analogies

6.5.2.1 Recruitment

Four subjects volunteered from our local lab setting.
6.5.2.2 Procedure

1. Subjects were told to listen to a series of sound clips. They were told to associate, if possible, these sounds with their dominant arm, to make a movement with that arm, and to what degree the sound felt like it was an "intuitive pairing", both in terms of just understanding the sound, and in terms of the mapping between the sound and themselves.

2. After this sequence, subjects were moved through a motion akin to a bicep curl and fist raise, and lowering of their arm back to the table. They were told they could use sounds from the library of collected sounds as well as sounds that felt better to them.

3. Lastly, subjects were placed in an interactive environment. Raising and lowering their arm above a distance sensor platform. The platform made discrete sounds that triggered at intervals of five centimeters upwards and downwards. Clear and sharp sounds were played while rising their arm, while fuzzy and noisy sounds were played while lowering it. Participant responses were recorded.

The subjects were played a random ordering of the following sounds.

<table>
<thead>
<tr>
<th>Number</th>
<th>Sound Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ball bouncing</td>
</tr>
<tr>
<td>2</td>
<td>Sharp inhale followed by single bounce</td>
</tr>
<tr>
<td>3</td>
<td>Wrinkled and stretched leather</td>
</tr>
<tr>
<td>4</td>
<td>Ratchet tool ratcheting quickly</td>
</tr>
<tr>
<td>5</td>
<td>Ratchet tool ratcheting slowly</td>
</tr>
<tr>
<td>6</td>
<td>Air released from high pressure</td>
</tr>
<tr>
<td>7</td>
<td>Shaky breathing followed by stretched leather midway</td>
</tr>
<tr>
<td>8</td>
<td>Stretched leather followed by shaky breathing</td>
</tr>
<tr>
<td>9</td>
<td>Servo quickly moving back and forth</td>
</tr>
<tr>
<td>10</td>
<td>Hollow weight being dropped</td>
</tr>
<tr>
<td>11</td>
<td>Airplane taking off, passing by quickly, and landing</td>
</tr>
</tbody>
</table>

Table 16: Sounds played during preliminary Audio-Movement Congruence study

Subjects then were asked to describe and demonstrate the body motion of their arm as described by the sound they heard.

6.5.2.3 Implementation of Interactive Sound Generator

We implemented the interactive physical sound system using a Beaglebone Black and BELA music generator board. Sounds were recorded
locally and interactive sound generating code was developed in Pure Data.

![Prototype for Interactive Sound-Movement Testing](image)

Figure 19: Prototype for Interactive Sound-Movement Testing

See Appendix reference for implementation detail.35

6.5.2.4 Results

Movement Descriptions from Sound

6.5.2.5 Qualitative Results

For Part 1, where participants listened to the sounds above and replied with a movement of their arm and an associated description, we recorded whether for each sound, the participant’s reply appeared motion dominant or speech dominant to the researcher. That is, when responding, did they mostly describe the sound in words or with movements. Taking majorities:

Participant 1 described themself as coming from an engineering background with a close association to sound from playing videogames. Participant 2 described themself as simply, a mechanical engineer. Participant 3 described themself as an animator. Participant 4 described themself as an interaction designer.

Participant 1 tended to describe most sounds with movement. The sounds they claimed felt most "intuitive" were sound 11: "Airplane taking off, passing by quickly, and landing", and sound 3, "wrinkled and stretched leather." They felt sound 6 was the least relatable in terms of motion, followed by the combined sound profiles - 7 and 8.

Participant 2, in general, did not associate most sounds with movement. However, for sounds that were associated with tools, they asso-
7.6.5 Motivating a Notion of "Movement-Audio Congruence" by Visual-Audio Congruence

<table>
<thead>
<tr>
<th>Number</th>
<th>Sound Description</th>
<th>MD</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ball bouncing</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Sharp inhale followed by single bounce</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Wrinkled and stretched leather</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Ratchet tool ratcheting quickly</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Ratchet tool ratcheting slowly</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Air released from high pressure</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Shaky breathing followed by stretched leather midway</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>Stretched leather followed by shaky breathing</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Servo quickly moving back and forth</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Hollow weight being dropped</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Airplane taking off, passing by quickly, and landing</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 17: Movement Dominant (MD) and Speech Dominant Responses (SD) to Played Sounds. Value for each indicates how many people were judged to describe sounds with mostly movement, or mostly words.

...associated the action movement of the tool - sounds 4 and 5. Interestingly, they also associated the taking off airplane with motion. Uniformly, they said that they did not feel like the other sounds were relatable in terms of motion.

Participant 3 described many sounds as if they were large film props with exaggerated motions. They commonly moved their arm and claimed that the sounds reminded them of "pulling large levers", or "creaking doors." They found strong movement association with 3 - wrinkled leather, 9 - servo quickly moving back and forth, and 11, the airplane taking off, passing by quickly, and landing. They found least movement association with sound 6 - air released from high pressure, although they described it by hissing.

Participant 4 appeared very sleepy. They found sounds 3, 4 and 5 to be most relatable in terms of movement, making small twisting motions for each. They found sound 6 and sounds with shaky breathing - 7, and 8 to be least relatable, but also remarked that they found those sounds, "unnerving."

Sound Descriptions from Movement Each participant was guided into a motion akin to a bicep curl followed by a fist raise, and asked to make sounds describing the motion.

Participant 1 described the motion in terms of sound 9, the servo. Participant 2 described the motion in terms of sound 5, the rachet. Participant 3 created a new sound from their mouth, which they described after making the sounds as a large lever being pulled, before pulling a horn in a train. Participant 4 had trouble coming up with a fitting sound. With some back and forth, they decided that sound 5,
the ratchet was closest to describe the bicep curl motion, and created a small "tah" sound for raising their fist.

Interactive Sound Generation

Lastly, participants interacted with a device that directly sonified the movement of their right arm up and down at discrete levels. Moving their arm up resulted in the playing of a sharp, clear, and discrete sound. Moving their arm downwards resulted in a fuzzy, discrete sound.

Participant 1, after a few seconds moving their arm in the interactive space, said that moving up felt like "stacking lego blocks", and moving downwards was like "digging in Minecraft". They felt as if the sounds created a pressure moving downwards, and a "positive clarity" moving upwards.

Participant 2 spent about 1 minute moving their arm in the interactive space. They felt like the discrete property of the rising sound described individual pegs on a ratchet. They said the sound played while lowering their arm felt confusing and stressful, like "something breaking". They felt as though they did not want to place their arm downwards at all.

Participant 3 spent a few seconds moving their arm in the interactive space and appeared excited. They felt movement up was positive and felt like "building up something," while lowering their arm felt "less clear, kind of like pulling up a rug."

Participant 4 spent about thirty seconds moving their arm in the interactive space. They felt like they "liked the discrete steps rising" and "did not like the steps falling." They felt like the sounds played when lowering was not as discrete, and created a sense of resistive pressure when moving into it.

6.5.2.6 Discussion

Interestingly, we found that users described analogies and associations that, to a degree, matched with their background of experiences with sounds and objects. For example, Participant 1 described the interactive experience in terms of "Lego Blocks" and "Minecraft," where they had mentioned that they came from an engineering background and played many video games, while Participant 2 tended to describe all motions in terms of tools used on an engineering workbench. Participant 3 appeared to associate sounds as they are used in animated mediums; exaggerated with larger-than-life props. Participant 3 felt that the motion that they were asked to make in 6.5.2.5 could be described as "pulling large levers."

Curiously, all participants had some motion association with sound 11, the sound of an airplane taking off, cruising, and landing. In addition participants had very little motion association with sound 6, the sound of pressure being released from a pipe.
These observations suggest that people may more easily relate motion of their own bodies to the sounds of relatable, moving physical objects than less tangible phenomenon such as steam. Pressure being released from a pipe does not have a solid body, and perhaps this distorts a physical association of body with movement of the air.

Lastly, clarity vs. ambiguity for the played sounds in the interactive scenario appeared to provide a sense of directional movement and pressure.

At a very preliminary stage, these observations provide some insight into how different people think about sounds as analogies. Building off of this basic work, we discuss a system of how people can insert interests, which become translated into customized movement analogies. The customized movement analogies could be combined with high level goals for implicit learning and used to create specialized feedback profiles for learning movement specialized to individual people. This result is interesting, if not surprising, as it has previously been shown that previous experiences affect the process in which people formulate problems and transfer learning to new experiences.

6.5.2.7 Limitations

As a preliminary study with four participants, the results of this exercise provide some potential avenues to explore in the future, but do not yield any statistically significant results. Furthermore, ratings regarding movement dominant or speech dominant scores should be coded and reviewed by at least three reviewers total.
CONCLUDING REMARKS

7.1 CONCLUDING REMARKS

Originally, we set out to understand if we could help newcomers to skills learn unfamiliar movements. To do so, we laid out and tested a strategy for implicit learning using auditory feedback driven by high-level goals. We designed, implemented, and demonstrated a system capable of simplifying a complex motion into a high level performance objective. We suggested and proposed feasible methods of breaking down complex motions into similarly simplified models for auditory feedback generation. Within a user study, we integrated the system into a gymnastics training procedure alongside coaches for inexperienced participants. Mental Model vs. Performance results from this study anecdotally suggested that the coaching process facilitated implicit learning, and that use of the system resulted in greater consistency and lowered variability in performance improvements over controls. Towards the future, to extend the system beyond front flips, we proposed a user flow for using our system to generate useful feedback for general movement types. Lastly, to enable this system to work, we created an initial exploration that showed preliminary results on how different people perceive audio-movement analogies depending on familiar sound-object associations in their lives. We presented an initial foray into a possible future where feedback can be tailored based on individual experience to create sound analogies for movement description.

7.2 FUTURE APPLICATIONS

Learning an unfamiliar motion of oneself is not far from developing a schema for learning an unfamiliar relative motion of oneself and other entities; be them other people, machines, or the environment.

We believe that the work put forth here in this thesis may be expanded in a number of directions. The work put forth in this thesis primarily examined using partially obscured auditory feedback informed by physics models to aid in learning unfamiliar athletic movements. We think these same principles can be applied to learning movement patterns and behaviors in various environments; competitive team dynamics, interacting with dynamically changing environments, and learning how to move together with machines.
7.2.1 Moving Together with Each Other: Implicit Understanding of Team Strategy

For athletes that train together as a team we can imagine using this system to develop a sonified relationship between people. We could combine biometric information and physical movement of teammates, such as in soccer, to project harmonic scale that completes towards reaching ideal strategy patterns defined by simulation. For example, for a soccer game, a simulation may capture ideal placement and endurance of various athletes. By training with only the sound of progression towards ideal strategy states, athletes may develop a procedural understanding of effective team play. This idea could carry over into a variety of team-based applications, such as military strategy, rescue team positioning, or assembly of medical surgical teams for example. By training with partially obscured feedback, team members could gain a strong sense of how to execute well as a team, and when team efforts are succeeding or failing.

7.2.2 Moving in Sync with the Environment

There are vast array of environments that work and train in. For example in skiing, individuals encounter a variety of terrain. We could engage a simulation to project minimal energy states of the body’s movement (direction and speed) that work best with the environment at hand. As sound, we can project this minimal energy “syncing” as a high level goal through sound. If an individual matches the lowest energy state required to get through the course they would hear sounds indicating success and sync. Otherwise, they would hear sounds indicating tension, or lack of sync. By training with this partially-obscured high level energy observation, athletes would hopefully implicitly learn how to maneuver into lowest energy states of movement to move through the environment efficiently. This idea of syncing with the environment by using simulation to provide a high level observation, and using feedback to relay that high level goal to the user, could be translated into a variety of other people-environment applications. For the elderly, walking through a crowded area could engage a simulation that determines likelihood of falling. This likelihood could be projected as audio feedback, enabling users training with this system to gain an implicit understanding of when they need to be consciously cautious of stabilizing themselves. In unfamiliar environments requiring expert movement, such as in space, aerobatic movement through the air, or underwater, this projection of simulation results’ high level goals could result in implicit understanding of efficient movement through those spaces.
7.2.3 Moving Together with Machines

As we engage with future development of wearable robotics, exoskeletons and control of vehicles that have increasingly greater autonomy, it will likely be important that we can learn how to most effectively work with these machines. As these machines already engage in some degree of planning and simulation, individuals could directly sonify progress towards high-level machine high level objectives and gain an implicit feel for how to mostly effectively work with them, or change them. For example, as an exoskeleton encounters rough terrain, it may switch to a unique set of control algorithms to deal with the new terrain. By sensing the movement state of the wearer, discerning the minimal energy state required for efficient motion, and playing progression towards that minimal energy state as a high level goal, wearer’s could implicitly learn how to move most effectively with their suit. Likewise this principle could be extended to vehicles with a large amount of autonomous agency, such as future spacecraft and self-driving vehicles. Auditory feedback of simulation-determined high level goals could create a strong degree of sync and effective operation between pilot state and the future vehicles we engage with.

7.2.4 Developing an Auditory Feedback Language based on Analogy

Following our preliminary work in audio-movement congruence, we believe that future audio feedback systems can be delivered in a manner that makes significant sense to its user through use of contextually relevant sound analogies. To engage in this, we believe that feedback systems would first ask questions regarding user’s background and life experiences. From these experiences the feedback system would reach into a language of analogous sounds generated that fit the experiential profile of the user. Future work would study this relationship closely, and develop this experiential profile sound language for generating individually informative sound profiles. Combined with high level goals for implicit learning, the two system would possibly enable a rapid and awesome degree of implicit learning of unfamiliar movement, individually, as a team, with autonomous machines, and the ever-changing environment.
APPENDIX

8.1 USER STUDY QUESTIONS

1. How well did you sleep last night? How many hours?
2. How well did you eat today?
3. Are there any external stresses on you right now?
4. How did you feel about your progress today?
5. How well do you feel like you did today?
6. On a scale from 1 to 5, where 5 is most, how much control did you feel over your actions?
7. If you did not perform flips today - substitute "flip" with "hardest action" - e.g., somersault or dive roll - you performed today
8. On a scale from 1 to 5, where 5 is most, how afraid were you when performing the flips?
9. On a scale from 1 to 5, where 5 is most, how confident were you when performing flips?
10. Could you describe your best experience flipping today?
11. Could you describe your worst experience flipping today?
12. From your learning so far, could you describe how you properly execute a front flip? What makes a good front flip?
13. Was there anything from today’s learning that modified this understanding?
14. What actions that you take are most effective for achieving a high front flip?
15. What actions that you take are most effective for achieving a solid landing?
16. Could you describe how you felt coming in today? How you feel at the end of this session?
17. Any other interesting observations or feelings from today?
18. Could you describe the way you interacted with your training aid today? (sensor only)
19. Did it help you or get in the way? (sensor only)
20. Did it tell you anything about your performance? (sensor only)
21. Could you describe the relationship between your movement and the feedback you received from the training aid? (sensor only)
22. In replay, does hearing a sound correspond to your first-person experience performing the flipping action? If it does, can you describe it? If it does not, can you describe why? (sensor only)

8.2 USER STUDY: EVALUATION ENVIRONMENTS

8.2.1 Flip Environment 1

8.2.2 Flip Environment 2

8.3 TRAINING EXERCISES

1. Warm up - participants performed a jog around the facility, followed by stretches led by the coach.

2. Fall Training - participants began by tucking in their arms into their body and falling on a wedge mat. The coach emphasized keeping arms in towards the core, and never allowing arms to fall outside the motion, beyond the body. Coaches observed participants falling on an inclined wedge, and into a soft resi mat. Coaches typically demonstrated this motion in person before asking participants to try.

3. Forward Roll Training I: Incline from Top of Incline - participants were given verbal instruction to "Squat, Place hands down, Tuck in chin to chest, Roll." The use of the incline made use of gravity to aid participants gather forward momentum. In initial stages, coaches spotted participants to help them begin the roll motion. Once coaches observed participants were comfortable, participants continued performing the motion themselves, correcting based on feedback from coaches.

4. Forward Roll Training II: TumbleTrak to Resimat - Using the same verbal instructions as for Forward Roll Training I, participants performed a forward roll from the trampoline surface of the Tumbletrak onto a soft 24 inch thick polyurethane foam Resimat. Depending on performance in Forward Roll Training I, coaches may or may not spot for initial assistance. Roll motions here are unassisted, but made helped made safe by the Resimat.
Figure 20: Flip Evaluation Setting I - Each white line indicates +5 inches.
Figure 21: Flip Evaluation Setting II - Each white line indicates +5 inches.
5. Forward Roll Training III: Incline from Floor - participants stood in front of the high end of the incline, placed the hands on the top of the incline, and jumped off of the floor to initiate a forward roll down the incline. This forward roll required a strong jump from the floor, and is designed to train participant’s ability to generate force to drive the rolling motion, as well as their ability to keep space between their head and the surface beneath them.

6. Forward Roll Training IV: Trampoline to Elevated Surface - Two 8-inch polyurethane mats are stacked across the middle of a trampoline, leaving raw trampoline space on either side of the mat. The participant begins on the one side of the mats, and a coach on the other. Participants are instructed to use the trampoline to jump forward, with their arms securely “reaching high above and outward” towards the mat, and to perform a forward roll, when landing on the mat.

7. Forward Roll Training V: Forward Roll on a level surface. Hard surface to Hard surface - Participants performed a forward roll on the floor, starting from a standing position and ending in a standing position.

8. Dive Roll Training I: TumbleTrak to Incline - Participants on the tumbletrak, and bounce themselves over the incline.

9. Dive Roll Training II: Springboard Punch to Incline - Participants punch jump off of a springboard onto an elevated side of an incline.

10. Dive Roll Training III: TumbleTrak Punch over obstacle - Participants run, hurdle, and punch jump dive roll over an obstacle on tumbletrak.

11. Dive Roll Training IV: Floor Punch over obstacle - Participants run, hurdle, and punch jump dive roll over an obstacle on a spring floor.

12. Dive Roll Landing I: Elevated Surface to Floor - Participants initiate a forward roll off of an elevated mat, rolling onto the floor.

13. Punch Training I: Alternates between punching back and forth, and punching between mats. The punch describes the action of hitting the floor hard and using toes and calves to develop power.

14. Punch Training II: Hurdle sequence. The punch is incorporated into a run. End point is dive roll over an incline.
15. Flip Simulation I: Run the experience performing dive roll onto elevated surface mat. Launch via springboard.

16. Flip Simulation II: Trampoline with harness for complete spotted flip.

17. Flip Training I: Flip to back on Resi

18. Flip Training II: Spotted Full Flip on TumbleTrak


8.4 AUFLIP USE PROCEDURE

Figure 22: Using the AUFLIP Feedback System: Activation Pattern for Triggering Physics Model uses Demonstrated 3-step takeoff technique
Score  Degree of Understanding
1  No understanding
2  Little understanding
3  Decent understanding
4  Full understanding

Table 18: Mental Model Evaluation for Flip Descriptions

Score  Degree of Understanding
1  "Balk," or half-way give up. Applies to all skills.
2  Performed forward roll with low body control. Rotation may not have ended in feet down sta
3  Performed dive roll with low body control.
4  Good Dive Roll.
5  Full attempted but failed front flip.
6  Completed from flip with low body control.
7  Completed front flip with moderate body control, parabolic trajectory.
8  Completed front flip with high body control.

Table 19: Performance Evaluation for Flip Descriptions

Figure 23: Participant 1 Averaged Performance Scores Per Trial. Averaged
Performance Scores evaluate flips and flip attempts from the last
7 minutes of each session.
Figure 24: Participant 1: Rated Mental Model Score per Session. Mental Model scored by 3 experienced gymnasts according to rubric.

Figure 25: Participant 2 Averaged Performance Scores Per Trial. Averaged Performance Scores evaluate flips and flip attempts from the last 7 minutes of each session.
Figure 26: Participant 2: Rated Mental Model Score per Session. Mental Model scored by 3 experienced gymnasts according to rubric.

Figure 27: Participant 3 Averaged Performance Scores Per Trial. Averaged Performance Scores evaluate flips and flip attempts from the last 7 minutes of each session.
Figure 28: Participant 3: Rated Mental Model Score per Session. Mental Model scored by 3 experienced gymnasts according to rubric.

Figure 29: Participant 4: Average Evaluated Flip Performance per Session. Averaged Performance Scores evaluate flips and flip attempts from the last 7 minutes of each session.
Figure 30: Participant 4: Rated Mental Model Score per Session. Mental Model scored by 3 experienced gymnasts according to rubric.

Figure 31: Participant 5: Average Evaluated Flip Performance per Session. Averaged Performance Scores evaluate flips and flip attempts from the last 7 minutes of each session.
Figure 32: Participant 5: Rated Mental Model Score per Session. Mental Model scored by 3 experienced gymnasts according to rubric.

Figure 33: Participant 6 Averaged Performance Scores Per Trial. Averaged Performance Scores evaluate flips and flip attempts from the last 7 minutes of each session.
Figure 34: Participant 6: Rated Mental Model Score per Session. Mental Model scored by 3 experienced gymnasts according to rubric.

8.5 USER STUDY PERFORMANCE EVALUATION RUBRICS

8.6 USER STUDY RESULT PLOTS

8.7 USER STUDY OBSERVATION LOGS

8.7.1 Participant 1 Observations

8.7.1.1 Session 1

Pre-Trial Participant 1 arrived early. They slept 10 hours the night prior, with a stress level of "very little stress". When asked about how a front flip functioned, they were "not sure if they could do it."

Safety Baseline Participant 1 demonstrated an ability to fall safely and perform a forward roll with minimal instruction.

Training Progression Following the training procedure outlined by Phase I and Phase II, they worked through a progression from forward roll to dive roll. During this time they rotated between the following drills, working through the progression as the instructor felt they were sufficiently comfortable to transition.

- Fall Training
- Forward Roll Training I: Incline from Top of Incline
- Forward Roll Training II: TumbleTrack to Resimat
APPENDIX

- Forward Roll Training III: Incline from Floor
- Forward Roll Training IV: Trampoline to Elevated Surface
- Dive Roll Training I: TumbleTrak to Resi
- Dive Roll Training II: TumbleTrak to Elevated Incline

Post-Trial From Questionaire, Participant 1 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 1 out of 4 with a std deviation of 0. Reviewer’s average performance judgement score was 2 out of 8, with a std deviation of 0.774.

Post Trial, Participant 1 felt like they "learned how to roll and jump in a very safe way." To perform good forward roll, they felt they learned that "you [need to] push with your hands, [arms] should be really straight, and [your] chin should be tucked down, because you need to protect your neck and make a diving movement. And jump higher. Try to tuck your hands inside." They felt as though the instructor helped them learn most. They found that drills around hand and arm placement were most helpful, by the end they felt they "could finally feel the difference between bending my arms and not." They felt like they had never experienced anything like this experience before, and found the experience "very fun and exciting."

8.7.1.2 Session 2

Pre-Trial Participant 1 arrived early. They slept 7 hours the night prior, with a stress level of "zero". When asked about how a front flip functioned, they stated that they needed to "jump higher."

Training Progression Following the training procedure outlined in Phase II, they advanced from dive roll towards performing basic front flips.

- Warmup Stretch
- Dive Roll Training I: TumbleTrak to Incline
- Flip Simulation I: Spring Board to Elevated Mat
- Punch Training I: Repeated Floor Jumps
- Flip Simulation II: Trampoline with harness for complete spotted flip.
- Flip Training I: Flip to Back TTrack to Resi
- Forward Roll Training I: Incline from Top of Incline
Of note, for Dive Roll Training I, Participant I stated they felt afraid of placing themselves completely in the air, and stopped themselves right as they approached the incline or as they attempted to execute the skill. The coach added two elements of feedback to help with this; 1) the coach placed a pool noodle above the incline, and asked Participant I to pretend a wall extended to the height of the noodle that they needed to dive over, and 2) as Participant I approached the incline, the coach shouted, "Go!" at the point of action. Performance appeared to improve after these additions. Participant I managed to place their body fully in the air and perform a dive roll of adequate quality to the coach. The coach asked the participant, "What felt different," to which the participant replied, "I now know the feeling of being in the air." When transitioning to the Flip Simulation I: Spring Board to Elevated Mat Drill, the participant also exhibited some difficulty in rising to the elevated mat. The coach lowered the elevation of the mat, and told the participant to be "explosive with [their] lower body." To help with this, Participant I engaged in Punch Training I drills. With successful results, Participant I moved through towards Flip Simulation II on trampoline, but the coach felt they did lacked some body control and appeared to have difficulty balling up in flip. Hence, to finish the session, Participant I reperformed Forward Roll Training I, with emphasis on keeping tight and rounded. Performance evaluation was performed for the last 7 minutes of Flip Simulation II.

Post-Trial From Questionaire, Participant I rated their overall feeling from the day as 4 out of 5, control over their actions as 5 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 3 out of 4 with a std deviation of 1. Reviewer’s average performance judgement score was 4.7 out of 8, with a std deviation of 2.

Post Trial, Participant I felt like they "learned how to do [a] flip with the belt [harness]." They mentioned that using it felt like "being in slow motion so [they] could control [their] body," and that this feeling of slow motion made them "have more confidence [in] control[ing] [their] body in the air." To perform a front flip, they described the experience as "Jump[ing] higher [with] good timing to tuck ... knees and stretch arms," also "apply[ing] more force to rotate [their] hip." Interestingly, they said that nothing from the session affecting their understanding of how to perform a good flip. They felt the most difficult element for them was to "...get the timing when ... tucking [their] knee and touch[ing] [their] arm in order to make a higher jump." Lastly, they expressed excitement over the new experience and feelings, "This is so fun. I feel like I’m flying!" They felt like they could not relate the experience to previous experiences in their life.
8.7.2 Participant 2

8.7.2.1 Session 1

Pre-Trial Participant 2 arrived on time. They slept 7 hours the night prior, with a stress level of "zero". When asked about how a front flip functioned, they stated that they "had no idea."

Training Progression Following the training procedure outlined in Phase II, they advanced from dive roll towards performing basic front flips.

- Warmup Stretch
- Fall Training
- Forward Roll Training I: Incline from Top of Incline
- Forward Roll Training III: Incline from Floor
- Punch Training I: Repeated Floor Jumps
- Dive Roll Training II: Hurdle Sequence Punch to Incline
- Flip Simulation I: Spring Board to Elevated Surface

Of note, Participant 2 appeared to have very good body control throughout all movements. During Forward Roll Training I, when first teaching the forward role, the coach had the participant following in sync with their demo, while they synchronously repeated, "push...and tuck!." During Punch Training I and Dive Roll Training II, the coach demoed the motion sequence and then broke it down into parts; the punch, the hurdle, and run. The coach performed all drills together with the participant, verbalizing the sequence synchronously with the motions created. When putting them together, the participant was confused. The coach then removed and added back elements, simplifying the motion, and kept on synchronously providing feedback, "Step 1, Step 2...then Jump!" with emphasis on the words as the coach performs the motion. The last seven minutes of dive roll drills were recorded for evaluation.

Post-Trial From Questionaire, Participant 2 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer's mental model score for their understanding of the front flip was 2.33 out of 4 with a std deviation of 0.54. Reviewer's average performance judgement score was 2.6 out of 8, with a std deviation of 0.57.

Post Trial, Participant 2 felt like they appreciated "[how]... the coach broke it down so [they] [could] learn it progressively." They came in "with no idea" and left "confident to go to next steps." They took away
that the most important action to be taken during a front flip is a "powerful jump." With regards to how to execute a front flip, Participant 2 wrote that "Confidence and body control make a good flip." The described the important parts of landing the skill as being "mindful of where [landing]," and "be[ing] prepared." From their session they felt that "Any complicated movement can be broken down into simpler steps." Lastly, they stated having never felt anything or had any similar experiences to their training session.

8.7.2.2 Session 2

Pre-Trial Participant 2 arrived on time. They slept 7.5 hours the night prior, with a stress level of "zero". When asked about how a front flip functioned, they stated that they "felt more confident"

Training Progression Following the training procedure outlined in Phase II, they advanced from dive roll towards performing basic front flips.

- Warmup Stretch
- Forward Roll Training V: Forward Roll on a hard level surface.
- Flip Simulation I: Springboard to Elevated Mat
- Forward Roll Training III: Forward Roll from floor to incline
- Dive Roll Training IV: Floor Punch over Obstacle
- Dive Roll Training III: TumbleTrak Punch over Obstacle
- Punch Training II: Hurdle Sequence Punch to Incline/Elevated Mat
- Flip Training I: Flip to back on Resi

Of note, Participant 2 appeared to continue to have good body control throughout most movements. In the beginning of the session, the coach had Participant 2 perform Forward Roll Training I, Flip Simulation I, and Forward Roll Training III back and forth, performing roughly 3 rounds of each in sequence. During Dive Roll Training IV, the coach identified that Participant 2 felt uneasy being completely airborne. The coach gave three tips to try to help with this; 1) the coach provided an exercise that required the legs to be raised vigorously, to help the participant feel the exertion pattern that would help them get enough force to get safely airborne, 2) the coach placed a target line on the ground with chalk, and told the participant to look up and out reach outwards; tucking in their chin when they saw the line, and 3) the coach placed an obstacle that the participant would physically have to jump over, and that by being there forced the participant to become airborne. The steps appeared to help; once the participant...
performed dive rolls with this airborne component, they appeared to 
exhibit much less uneasiness with the motion. To move Participant 
2 towards performing a flip, the coach raised a pool noodle obstacle 
during Punch Training II, having the participant dive roll over the 
obstacle. The coach gradually raised the obstacle, and asked the par-
ticipant after engaging in this action for roughly ten turns, to drive 
their heels harder. The participant resultantly ended up performing 
a flip to their back from the tumble track to resipit (Flip Training I), 
and then on their own showed they were able to perform that action 
without obstacle training aids.

Post-Trial From Questionaire, Participant 2 rated their overall feel-
ing from the day as 5 out of 5, control over their actions as 4 out of 
5, level of fear they experienced as 5 out of 5, and confidence in their 
ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front 
flip was 2.66 out of 4 with a std deviation of 0.57. Reviewer’s average 
performance judgement score was 4.6 out of 8, with a std deviation 
of 0.94.

Post Trial, Participant 2 felt like the feeling exercise the coach gave 
them was really important. They stated that they "did not know [that 
they] need[ed] the initial momentum...[the] coach gave me [an] ex-
ercise for butt and abs." "Remember[ing] [the] exercise feeling [was] 
really important." Their initial feeling of the flip was that it was a "bit 
dizzy." They felt like the best part of the experience was "no having to 
land on [their] hands anymore", with the greatest challenge being that 
"it was hard to get the initial angular momentum." They described the 
front flip as "A big jump reaching far," followed by "fold[ing] your 
stomach to get ... initial momentum," and then "grabbing knees to 
finish the roll." They mentioned that it significantly helped to "reach" 
during the initial jump, and to spot a target before landing. Lastly, 
they found that the flipping experience "was a bit dizzy" and that it 
reminded them of "doing a handstand where you kick hard," which 
they had experienced from alternate athletic activites.

8.7.2.3  Session 3

Pre-Trial Participant 2 arrived on time. They slept 7 hours the night 
prior, with low to no stress. When asked about how a front flip func-
tioned, they stated that they "felt like they could do it"

Training Progression Following the training procedures outlined in 
Phase II and phase III they advanced from basic flips to flip evalua-
tion. Participant 2 was randomly chosen to perform with the feedback 
device.

• Warmup Stretch
• Flip Simulation I: Springboard to Elevated Mat
8.7 User Study Observation Logs

- Flip Training I: Flip to back on Resi
- Flip Training IV: Augmented Flip Training: TTrack to Elevated Resi

Of note, Participant 2 warmed up with the Flip Simulation I drill, to evaluate punch ability and comfort through the motion. Showing consistent performance, the coach placed Participant 2 on a modified variant of Flip Training I: standing at the edge of the resi, and without jump performing a flip to back. Showing success, Participant 2 was ready for final evaluation. Participant 2’s evaluation came later in the study, where for safety purposes participants flipped onto an elevated resi to reduce complexity of the landing. Participant 2 wore the AUFLIP feedback device on their right ankle during Flip Training IV, and was evaluated for performance during the last seven minutes of Flip Training IV. During use of the AUFLIP feedback device, the participant was advised that they could check the video footage of their performance at any time; the did so with initial use of the system, reportedly to “understand approximately what the sounds meant” The researcher described the basic underlying workings, and also played an example of a “perfect sound,” with the explanation, “more sound is better.” To show the system worked per trial, if the system successfully detected takeoff and rotation, it reported visible values for takeoff speed and if rotation was detected on the iphone app. After initial observation of video at the session start, and discussing what it meant, in terms of performance, they did not view the video again.

Post-Trial From Questionaire, Participant 2 rated their overall feeling from the day as 5 out of 5, control over their actions as 5 out of 5, level of fear they experienced as 5 out of 5, and confidence in their ability to perform actions as 5 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 3.33 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 6.5 out of 8, with a std deviation of 1.0.

Post Trial, Participant 2 felt excited they finally were able to "Do a front tuck and land on the mat," and that they felt, "very good progress." They further felt like "As usual, quite nervous - the first try was the hardest." With regards to using the feedback system, the participant was bothered by specific takeoff pattern required to use the device - "The sensor required I take off ending on my left foot. I’m more used to taking off with my right foot," and suggested switching leg location for the next trial. Compared to previous sessions, the user felt the focus of the day became, "What I felt differently [was] focusing on jumping high...and forward. Us[ing] the lower body to propel the jump." In describing the front flip they stated, "First you need a powerful jump and focus on the butt. Then try to reach your
arm far, fold your stomach and bring your leg close to your butt. A powerful jump is the key." The description remained relatively unchanged from the previous session, albeit the last phrase changed from "initial momentum is key" to "power jump is key." Participant 2 was asked additional questions by questionnaire regarding their experience with the feedback device. In terms of wearing the device, they "didn’t really feel it in the movement." When asked if it helped them or got in the way, Participant 2 replied, "I got some feedback after on flip. It [would] be better if the feedback is more clear." They also commented that while it did help them with their performance and they felt they did "pretty well", "the sound helped, but the signal [meaning] is not so clear." They further stated, "The feedback comes right after the movement which is very good but the signal [meaning] is not clear enough." They felt that although, "the movement involves two parts, jump and roll, ... the feedback [did] not specify ... which part I did well and which I didn’t."

8.7.2.4 Session 4

Pre-Trial Participant 2 arrived on time. They slept 7.5 hours the night prior, with low to no stress. When asked about how a front flip functioned, they stated, "Powerful jump, not just high but also a bit forward. Try to squeeze your body and finish the rotation."

Training Progression Following the training and evaluation procedure outlined in Phrase III they performed flip evaluation. Participant 2 was randomly chosen to perform with the feedback device.

- Warmup Stretch

- Flip Training IV: Augmented Flip Training: TTrack to Elevated Resi

Of note, Participant 2 began performing Flip Training IV: Augmented Flip Training shortly after warming up. As opposed to session 3, they wore the AUFLIP on their left ankle, to enable them to take off on their right foot. As demonstrated throughout the trials, they appeared to maintain good control over their body movement. During use of the AUFLIP feedback device, the participant was advised that they could check the video footage of their performance at any time; again, they did so with initial use of the system. During trials, Participant 2, made a significant number of comments, calling out how many notes they heard relative to how they felt. Participant 2 checked the video recordings midway, reviewing two of them with the researcher and to reaffirm approximately how they felt the sound matched with performance. Before the feed, they mostly called out the number of notes they heard, and later after reviewing the video recordings, their feelings of performance. Such as, "I heard two sounds, 5.0 m/s - thought I did well - head didn’t touch. The sound is
consistent with my own feeling." "2.95 m/s, three sounds, felt delayed rotation felt good." During a few trials, the system failed to register the takeoff, or was triggered by a takeoff pattern that did not match the designed one. Without some reaffirmation by the researcher that the device had misfired, these moments appeared to be misinterpreted as bad performance, "1.8 m/s, I didn’t jump high enough no sound." Participant 2 appeared to perform consistently throughout the trial; while visibly maintaining good body control, they never "bailed" or gave up in the middle or when approaching the flip.

Post-Trial From Questionaire, Participant 2 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 5 out of 5, and confidence in their ability to perform actions as 5 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 2 out of 4 with a std deviation of 0. Reviewer’s average performance judgement score was 6.7857 out of 8, with a std deviation of 0.8926.

Post Trial, Participant 2 felt like the generated sound, "helped, it was consistent with my own feelings. It reaffirmed how I think." They commented that while it did help them affirm when they did or did not do well, "When I did not do well, I did not know when I did well." Participant 2 felt that after today, Their "skills were improved." Interestingly, they described their best experience during the session as, "Jump[ing] Higher" and their worst experience during the session as, "Not knowing how to jump higher." They described "Jump[ing] higher and roll[ing] faster" as critical for executing a front flip. From their experience with feedback system, they stated, "I used to think that I should jump higher and more forward. With the help of the sensor I realized that jumping higher is more important and a little bit forward is enough." To perform a high front flip, they mentioned that "placing arms up is helpful," and spotting the floor is important for landing. They felt like the AUFLIP system helped significantly with their learning, and that the "sound and score are helpful." Although they did not use replay frequently, they felt it helped initially acquaint them with the general relationship between sound and performance, "When the sound indicated that I didn’t do well I didn’t quite know how to improve. After watching the replay I understood how I did wrong and the sound ma[de] a lot of sense."

8.7.3 Participant 3

8.7.3.1 Session 1

Pre Trial Participant 3 arrived early. They slept 6-7 hours the night prior, with a stress level of "moderate," listing out a few work-related tasks they had to complete. When asked about how a front flip func-
tioned, they described it as "Kind of tuck and let your body fall over and land on your feet."

*Training Progression* Following the training procedure outlined by Phase I and Phase II, they worked through a progression from forward roll to dive roll. During this time they rotated between the following drills, working through the progression as the instructor felt they were sufficiently comfortable to transition.

- Warmup Stretch
- Fall Training
- Forward Roll Training I: Incline from Top of Incline
- Forward Roll Training II: TumbleTrack to Resimat
- Forward Roll Training IV: Trampoline to Elevated Surface
- Punch Training I: Repeated Jumps
- Dive Roll Training I: TumbleTrack to Resimat
- Dive Roll Training II: TumbleTrack to Elevated Incline

Of note, with Participant 3, the coach frequently made use of synchronous verbal feedback with describing body motions and live demonstrations of the skill together with the participant during training. For example, when performing forward rolls down the incline matt during Forward Roll Training I, the coach demonstrated the skill, and as the participant performed the skill, verbally called out what to do during the properly timed moments of execution: "Squat, arms down, roll". The coach consistently gave Participant 3 the correction of keeping their body in a ball shape, as Participant 3 had a tendency to "open" their body, which disrupted movements. The participant appeared least comfortable on the trampoline surface during Forward Roll Training IV, and attempted to rush the motion initially, becoming visibly more comfortable with repetition and advice. The coach gave advice that the motion should "Feel like diving, pretend something is right in front of your body," and that the participant’s movement would "Go where [his] arms are going." The participant mentioned that when they failed to complete the drill, they were "overthinking" as a result of "not wanting to fall off the trampoline, and going too far." The coach then took participant 3 to practice entry into the dive roll through repeated, controlled jumps on the tumbletrak - Punch Training I. As the participant engaged in the drill, the coach shouted in sync, "Jump, jump, jump, roll!" End evaluation was performed by participant 1 attempting dive rolls down an incline in the evaluation space from the jumping pattern; jumping from the tumbletrak surface, rolling down the incline into the soft resimat. The participant was observed to have an issue with keeping their arms out during the
end portion of the roll. When asked, they said that they felt like they were doing it because in Olympic Gymnastics they "saw gymnasts always put their arms out in landing". The coach remarked, "Interesting - in the beginning you said you need to keep your arms in for safety, but in actual practice your body somehow associates your idea of gymnastics from what you've seen." Dive rolls and dive roll attempts from the last seven minutes of this session was recorded for evaluation.

Post Trial From Questionaire, Participant 3 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer's mental model score for their understanding of the front flip was 2.33 out of 4 with a std deviation of 0.57. Reviewer's average performance judgement score was 2.71 out of 8, with a std deviation of 0.48.

Post Trial, Participant 3 felt like over the session they, "learned a lot about doing flips." From the start of the session, they felt they understood the movement better, as "more of a tuck...getting to the right height and ... allowing your bottom half to fall over your front half, that way you are safe when landing." They felt like the hardest element they encountered was "no letting their arms splay outwards or bend towards the middle of their body" during the motion. Interestingly, the session related to a previous experience of theirs from childhood; the participant described, "As a kid I saw video game characters do a barrel role...I didn’t quite understand it." "Now I feel like I do." During these descriptions, the participant made extensive use of 1st person body gestures to describe the rolling motion they saw.

Participant 3 also felt like the padding and gym equipment really helped their training, "As odd as this motion may seem, it's safe! So good motion!" They felt that live demos were helpful, as they could see how "some small things going wrong have large effects." Participant 3 described their best experience as the novel feeling of "using the springboard to flip over the wedge", and their worst experience as "almost falling off of the trampoline". They described a good flip as achieving the "right tuck and height to be able to get through the rest of the flip," with the actions that help most as, "getting a good jump" and "following with arms."

8.7.3.2 Session 2

Pre Trial Participant 3 arrived early. They slept 6-7 hours the night prior, with a stress level of "moderate," listing out a few work-related tasks they had to complete. When asked about how a front flip functioned, they described it as a "Forward leaning sort of jump, tucking into a midair fall, legs fall over torso and then a landing."
Training Progression Following the training procedure outlined by Phase II, they worked through a progression from dive roll to front flip. During this time they rotated between the following drills, working through the progression as the instructor felt they were sufficiently comfortable to transition.

- Warmup Stretch
- Punch Training I: Repeated Jumps
- Dive Roll Landing I: Elevated Surface to Floor
- Dive Roll Training III: TumbleTrak Punch over obstacle
- Flip Simulation I: Run the experience performing dive roll onto elevated surface mat. Launch via springboard.
- Flip Simulation II: Trampoline with harness for complete spotted flip.
- Flip Training II: Spotted Full Flip on TumbleTrak
- Flip Training IV: Free Flipping TTrak to Elevated Resi.

Post Trial From Questionaire, Participant 3 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 3 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 2.66 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 2.71 out of 8, with a std deviation of 0.48.

Commentary "When I did my first successful frontflip on the belt and again on the track. Using the springboard and nearly tipping the mat over. A strong kick giving you good height, a tuck that carries your forward momentum and the landing that keeps you safe from going too far. The landing is something that is learned from more rounds, keep knees bent to prevent falling, and hands are up to allow for energy post flip to be taken. The kick and the tuck are the most important for making the flip happen. Landing is important to keep you able to flip. Controlling how far forward your flip goes. Keeping it from going excessively far. I felt a bit nervous as I expected to get a flip done. I feel really proud of my progress! Front flips feel interesting. The feeling of inversion comes and vanishes very quickly."

8.7.3.3 Session 3

Pre Trial Participant 3 arrived early. They slept 6 hours the night prior, with a stress level of "moderate," listing out a few work-related tasks they had to complete.
Training Progression Following the training procedures outlined in Phase II and phase III they advanced from basic flips to flip evaluation. Participant 3 was randomly chosen to act as a control.

- Warmup Stretch
- Punch Training II: Punch Hurdle
- Flip Training III: Free Flipping TTrak to Resi.

Post Trial From Questionaire, Participant 3 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 5 out of 5, and confidence in their ability to perform actions as 5 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 3.33 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 5 out of 8, with a std deviation of 1.69.

Learning how the bounce feels when it’s good enough to do a flip. Worrying about flipping too far forwards. Getting a good initialization, nice tuck, following your motion and finishing it all out. The tuck determines how fast you rotate and that’s important for your landing. The initialization has a correct feeling for when you can make it into a flip. Having a redirection of momentum upwards to get the right height. Using that to also get your knees to tuck in enough to rotate yourself around. Having consistency for tucking and making it to your feet. I felt like I would be able to land on my feet faster than I did. I’m still expecting to improve my flip so that I can land properly. The feeling of useful motion is different than how it feels like before you don’t make the proper motion.

8.7.3.4 Session 4

Pre Trial Participant 3 arrived early. They slept 6 hours the night prior, with a stress level of "moderate," listing out a few work-related tasks they had to complete.

Training Progression Following the training and evaluation procedure outlined in Phrase III they performed flip evaluation. Participant 3 was randomly chosen to act as a control.

- Warmup Stretch
- Punch Training II: Punch Hurdle
- Flip Training III: Free Flipping TTrak to Resi.

Of Note: Visibly had difficulty reaching a parabolic trajectory. Tended to throw body forward rather than up.

Post Trial From Questionaire, Participant 3 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of
5, level of fear they experienced as 5 out of 5, and confidence in their ability to perform actions as 5 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 2.33 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 5.33 out of 8, with a std deviation of 1.87.

"The first landing on my feet. It was a high jump where I was paying more attention to my body than my eyes and flipping came more naturally. Not fully flipping and strangely falling sideways onto the mat. A good front flip has a jump, tuck, roll, and landing. The landing is focused on how well you tucked and the motion of your legs out of it. The tuck starts essentially just after the jump. Having a good jump and tucking after leaving the ground. Throwing your arms to get the motion up and over while your legs spiral you around. Tucking early enough to get all the way around and pressing your legs out while you’re in the landing. I felt pretty good. At the end of the session I feel like I made really good progress for figuring out how to do a front flip. Sometimes I wondered if I stepped into the crack of the mat and fell from that."

8.7.4 Participant 4

8.7.4.1 Session 1

Pre Trial Participant 4 arrived on time. They reported eight hours of sleep. When asked about how a front flip functioned, they described it as "Landing on my back if I tried."

Training Progression Following the training procedure outlined by Phase I and Phase II, they worked through a progression from forward roll to dive roll. During this time they rotated between the following drills, working through the progression as the instructor felt they were sufficiently comfortable to transition.

- Warmup Stretch
- Fall Training
- Forward Roll Training I: Incline from Top of Incline
- Forward Roll Training II: TumbleTrack to Resimat
- Punch Training I: Repeated Jumps
- Dive Roll Training I: TumbleTrack to Resimat

Participant 4 began the session with a warm up jog and stretches led by the coach. They asked if they were comfortable performing forward rolls. They said yes, and demonstrated one. The form of the forward roll came from other sports, defined by a sideways roll over
the shoulder versus the directly forwards roll performed in gymnastics. The coach then began teaching the participant the gymnastics type of role with a set of instructions and live demonstration. They used the instructions, "Squat, put your hands down in front of you, push through your legs, and butt," and had the participant repeat the sequence of motions without rolling multiple times until the coach felt the movement sequence had become ingrained. The coach then performed a second demonstration for the feeling of contacting the floor from the forward roll, by rolling onto their upper back with their body in a "hollow," or curled-in shape, instructing the participant to "feel this position - this is what you want to feel at the contact point." The participant initially appeared to have difficulty and reportedly found it difficult to land on their upper back and continue to roll. They repeated this motion with coach feedback, although still appeared to struggle to complete the roll to their feet. In response, the coach transitioned to another drill to help the participant gain rotation; the coach transitioned the participant to roll from the top of an incline mat. Before going, the coach informed the participant to "keep their arms in front of them, and use your momentum to carry you through to stand." After about ten turns, the participant was visibly comfortable rolling to stand. The coach found this rolling motion adequate, and proceeded to transition the participant to "Punch" drills - training the participant to deflect the gymnastics spring floor to yield upward force. To do this, the coach placed mats equally spaced along the floor, and the participant was tasked with stiffly jumping from mat to floor to mat without pausing. The participant appeared to have difficulty in harnessing power from the spring floor, performing bent knee jumps throughout. After about twenty attempted punches via this drill, the coach tried an alternate technique; without the mats, the coach guided the participant to jump backward and forward continuously, exerting force through the calves, not through bent legs. The participant proceeded to repetitively attempt this drill, with some improvement, but still yielding little upward height and using mostly bent legs. As a third strategy, the coach told the participant to try to "make as much sound against the floor as possible, make the floor make noise!" Within a few repetitions, the participant’s punching appeared to yield significantly more noise and upward jump height from the floor. The participant also appeared stiffer. Satisfied with this state, the coach transitioned the participant to perform a forward roll on the incline, starting with a punch from the floor. The participant was unable to complete this drill on their own for the first initial tries; the coach stepped in and hands-on spotted them to help. With spotting, the participant was able to complete the drill. To enable the participant to perform the drill on their own, the coach removed the jump-punch from the sequene and placed a block in front of the incline, increasing the ease at which the participant could punch into
the roll. The participant appeared more at ease, and their resultant motions appeared more fluid. The coach then reinstated the jump punch and removed the block; the participant was able to complete the movement and the coach was satisfied, reporting that the motion "Definitely looked smoother." The coach and participant lastly moved to the practice area to begin dive rolls from the tumbletrak onto the resi mat. The participant was unable to initially complete this motion, reportedly due to fear. The coach used a pool noodle as a visual height aid, and asked the participant to run and punch over the noodle. The participant managed to do so successfully around ten times, after which the session finished. 7 minutes of evaluation were taken prior to the final exercise, to evaluate the Participant 4's dive roll performance.

Post Trial From Questionaire, Participant 4 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer's mental model score for their understanding of the front flip was 2.0 out of 4 with a std deviation of 1.0. Reviewer's average performance judgement score was 2.1667 out of 8, with a std deviation of 0.7528.

Post Trial, Participant 3 felt that they "enjoyed breaking the motion down into parts that build[ing] it up." They found the biggest challenge of the day to be "Allowing [their] body to go through the motion of flipping. I'm mostly moving on the ground, its weird. I'm learning how my body moves and performs in the air, never done that before." They reportedly felt like their closest experience to learning to perform dive rolls was ziplining. According to the participant, confidence and fear played a large role in their ability to execute; "I learned, I just have to go for it. If I stutter, if I fall back, it doesn't happen." They felt their best experience was "learning the basics," and their worst experience was "panicking right before I had to perform." They felt like the could not quite describe how to execute a front flip just yet, but began using some gymnastics terminology in an attempt, mentioning that "you need to have a good punch with your hands above your head."

8.7.4.2 Session 2

Pre Trial Participant 4 arrived on time. They slept 8 hours the night prior, with a stress level of "none." When asked about how a front flip functioned, they described it as a "Takes initial steps with one last big step, feet together, hands out, and propel forward hands out pull torso over."

Training Progression Following the training procedure outlined by Phase II, they worked through a progression from dive roll to front flip. During this time they rotated between the following drills, work-
ing through the progression as the instructor felt they were sufficiently comfortable to transition.

- Warmup Stretch
- Punch Training I: Repeated Jumps
- Dive Roll Landing I: Elevated Surface to Floor
- Dive Roll Training II: Springboard Punch to Incline
- Flip Simulation II: Trampoline with harness for complete spotted flip.
- Flip Training II: Spotted Full Flip on TumbleTrak
- Flip Training IV: Free Flipping TTrak to Elevated Resi.

Of note: Tendency to punch forward rather than up. Appeared a little jittery. Bailed a few times. To overcome bailing, coach tried to visualize obstacles to rise above, mostly using a pool noodle.

Post Trial From Questionaire, Participant 4 rated their overall feeling from the day as 5 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 4 out of 4 with a std deviation of 0. Reviewer’s average performance judgement score was 5 out of 8, with a std deviation of 1.69.

Commentary "My best experience was feeling when my body was at the pinnacle just about to begin the flip. I felt weightless in that moment and it’s such an incredible feeling. My ‘worst’ experience was some embarrassing flops, but I laughed them off. To execute a front flip, you take some beginning steps, take your last big step like you are doing the long jump, punch the ground with both feet together and both arms above your head. Your feet, knees, hips, torso, and head should be aligned. When you punch the ground, wait until you reach the highest point in your jump, to tuck in your knees while leaning forward and bringing down your arms. Your rotation should speed up naturally. Be aware of where you are in the air and expect the landing. Prep your feet to land (and try not to knee yourself in the face!). Reaching the highest point in your jump and bringing your hips over to initiate rotation makes a good front flip (also, safety!) I learned the beginning foundations yesterday and today I learned the rest. I feel that a lot of this understanding is somewhat intuitive, but I gained more understanding by actually performing the flip. I take some steps, I imagine that I’m long jumping and then I imagine I’m stomping on a bug really hard. Also, when I jump, I imagine that with my hands I’m reaching for the pinnacle. As I’m coming out of the flip
I remember to flex my feet to prepare for when I apply pressure to the ground. I felt determined to front flip today and I did it. I felt less anxious today after yesterday’s session and more confident that I could achieve a front flip. I’m very proud of myself for going outside of my comfort zone and challenging my physical abilities. The coaches were incredibly supportive. They are great at breaking down the progressions of a front flip. I liked that we continued to work on dive rolls first before trying the front flip. I felt comfortable and safe the entire time. Most importantly, I had so much fun :)

8.7.4.3  Session 3

Pre Trial  Participant 4 arrived on time. They slept 7 hours the night prior, with a stress level of "none."

Training Progression  Following the training procedures outlined in Phase II and phase III they advanced from basic flips to flip evaluation. Participant 4 was randomly chosen to use the AUFLIP feedback system. During this time they rotated between the following drills, working through the progression as the instructor felt they were sufficiently comfortable to transition.

- Warmup Stretch
- Punch Training II: Hurdle to Punch
- Flip Training I: Flip to Back on Resi
- Flip Training IV: Free Flipping TTrak to Elevated Resi.
- Flip Training IV: Augmented Flip Training: TTrack to Elevated Resi

Of Note, Participant 4 was prepared to perform front flips, but appeared jittery. To warm up to the evaluation trials, Participant 4 was brought back through hurdle drills and warmed up to the evaluation environment a few repetitions before adding the feedback system. This was done because the feedback system requires a specific pattern of steps that add an additional layer of learning - the coach wanted to see that the participant was capable of executing with confidence first.

Post Trial  From Questionaire, Participant 4 rated their overall feeling from the day as 3 out of 5, control over their actions as 3 out of 5, level of fear they experienced as 5 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 3.66 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 4.5 out of 8, with a std deviation of 2.3805.
Commentary  My best experience was learning how to do standing flips. I enjoyed learning how to use my legs to propel myself to the height I needed to flip. I’m frustrated that I’m not getting the dive roll. I think I’m mentally panicking which is not allowing me to reach that moment of weightless just before I perform the dive roll. A good front flip has a strong punch/jump, body control, and rotation. First take two steps before going into a long jump and raise your arms above your head. Then punch the floor with your feet together. Your body should be aligned. Tuck and bring your arms in to give yourself rotation. Prep your feet to apply pressure to the ground and land with your knees apart so as not to knee your face, Yes. I learned a better way to approach the flip. It’s better that I take a very long, low jump into the punch. This will give me height and forward momentum. A low, long jump and a strong punch into the ground to gain height I make myself aware of where I am in the flip and once I know that I’m completing the rotation and nearing the ground, I prepare my legs for the impact I felt really excited coming in today to learn more. At the end, I felt frustrated because I haven’t gotten the dive roll and I felt I could have done better. None. Once I completed a flip, I would an auditory response and look at the band on my arm for the numbers. However, the numbers had no units or legends so I did not know what they meant until it was explained to me. It helped me understand how well I performed a flip and my elevation into the flip. The phone on my arm was easy to see and access. The one on my ankle bothered me a bit. I liked that I could control when the sensor took data. However, I think the sensor could be reset with a button on the phone rather than having to reach down and press the button on the board. Yes. It told me my elevation and whether I completed a flip If I completed a flip, the screen would read 100. Furthermore, it told me my takeoff speed which helped me know whether I need to work on my steps into the flip Yes it did. If I completed the flip, it displayed 100. If I didn’t it displayed 0. Plus, the auditory response would depending on my performance.

8.7.5  Participant 5

8.7.5.1  Session 1

Pre-Trial  Participant 5 arrived on time. They had 8.5 hours of sleep the night before. They experienced no stress. When asked about how a front flip functioned, they stated they had, “no idea.”

Training Progression  Following the training procedure outlined by Phase I and Phase II, they worked through a progression from forward roll to dive roll. During this time they rotated between the following drills, working through the progression as the instructor felt they were sufficiently comfortable to transition.
• Warmup Stretch
• Fall Training
• Forward Roll Training I: Incline from Top of Incline
• Forward Roll Training II: TumbleTrack to Resimat
• Forward Roll Training III: Incline from Floor
• Forward Roll Training IV: Trampoline to Elevated Surface
• Punch Training I: Repeated Jumps on TTrack
• Dive Roll Training I: TumbleTrack to Resimat

The participant began performing a warm up stretch routine guided by the coach. During the initial stretch training, the coach taught the base body positions - when asking what the basic gymnastics "tuck" body position was called, the participant called it "fetus." The coach remarked that the choice of words was "Interesting, especially because I usually the terms I hear are so commonplace that I've never heard anything different." The coach and participant then proceeded with safety fall training. The participant was first instructed to keep their arms in and around their body into the fall - they did so successfully on multiple padded surfaces. Deemed safe, the coach moved them to forward somersault training. With coach guidance, performed forward rolls down an incline wedge mat, and then from the Tumbletrak surface onto the soft Resi landing mat. The coach verbally called out what to do and what time: "Squat, arms down, roll". When deemed comfortable, the coach moved had the participant perform "straight jumps" on the Tumbletrak, ending in a forward roll on to the resi mat. During this period, the coach called out in sync with the actions, "Jump, Jump, Jump, Roll!" Once the coach deemed the participant comfortable enough with this drill, the participant became setup on the trampoline drill; performing a forward roll jumping off of the trampoline surface onto a stacked mat layered on the trampoline surface, and ending by rolling off of the mat back onto the raw trampoline surface. The coach emphasized, "pressure on hands," placement of the hands "reaching far out," and "keep[ing] tucked to stand coming out of the roll." During a few attempts, the participant appeared overly jerky and missed steps in execution. When asked, they stated that "They were trying to get momentum, by speeding everything up." Once Participant 5 achieved a motion the coach deemed satisfactory (within ten turns), the participant was taken back to the evaluation area - TumbleTrak and Resi mat - and asked to add a jump to the beginning of their roll to facilitate a dive roll. To aid in describing this process, the coach demoed the motion, and described the required actions as making a "Big Jump, keeping tucked all the way until the end, reaching far!" Participant 5 appeared comfortable
diving into the roll and rolling to their feet. However, they appeared hesitant to experience "air-time" or free fall by rapidly reaching downward for the mat rather than out far, and often did not have enough rotation to stand up at the end. Lastly, upon comments from the participant was concerned that they did not "stick" the landing the coach observed that "The language used to describe what’s happening and the ingrained conceptions of gymnastics is really interesting - [the participant] seems more fixated on this notion of “sticking it” than on informed corrections." Dive rolls and dive roll attempts from the last seven minutes of this session was recorded for evaluation.

Post Trial From Questionaire, Participant 5 rated their overall feeling from the day as 4 out of 5, control over their actions as 5 out of 5, level of fear they experienced as 3 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 1.6667 out of 4 with a std deviation of 0.7785. Reviewer’s average performance judgement score was 2.66 out of 8, with a std deviation of 0.577.

Getting over the fear at every stage. Doing something more difficult, fall and trip. Every time put wrists on the mat, that was the scary moment. Sometimes had to stop. Whenever I get over it happens and it happens quite naturally.

From Questionaire “Most similar: Rock climbing, when land tuck in and not hurt yourself. I ran a little on the trampoline, and rolled forward, fast, almost standing up in the end! Maybe the first few rolls I had my head impact on the mat. It was not fun! But then I learnt the trick I did a dive roll. The jump in the beginning is important to gain the momentum. The arms need to be kept straight, and head tucked under the arms as a good pivot. I learnt everything from today I’ll leave this one blank as I learnt a dive roll Having momentum in the beginning so when you end the roll, you’re on your feet, not on your back I was curious, a little scared. At the end I felt happy that I tried something new and did it well! Maybe I’ll explore gymnastics more?”

8.7.5.2 Section 2

Pre-Trial Participant 5 arrived on time. They had 8.5 hours of sleep the night before. They experienced no stress. When asked about how a front flip functioned, they stated, "Jump on a springy thing and I don’t know...roll?"

Training Procedures Following the training procedure outlined by Phase II-Phase III, they worked through a progression from dive roll to front flip.

- Warmup Stretch
- Forward Roll Training I:Incline from Top of Incline
Coach began with a low incline, raised incline progressively, boosting it higher with additional mats. Identified that participant needed to punch and rise higher before engaging in flips. Needed spot to get started with motion. Motions were decently smooth, more controlled by end of session.

Post Trial From Questionaire, Participant 5 rated their overall feeling from the day as 3 out of 5, control over their actions as 5 out of 5, level of fear they experienced as 4 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer's mental model score for their understanding of the front flip was 2 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 2.5 out of 8, with a std deviation of 0.83.

8.7.5.3 Session 3

Pre-Trial Participant 5 arrived on time. They had 7 hours of sleep the night before. They experienced no stress. When asked about how a front flip functioned, they stated, "Jump gaining enough momentum for the jump, getting the arms properly curved."

Training Procedures Following the training procedure outlined by Phase II-Phase III, they worked through a progression from dive roll to front flip. They were randomly chosen to wear the AUFLIP feedback device.

- Warmup Stretch
- Punch Training I: Repeated Jumps on Floor
- Flip Simulation I: Springboard to Elevated Surface
- Flip Simulation II: Trampoline with harness for complete spotted flip.
- Dive Roll Training II: Springboard Punch to Incline
- Dive Roll Training III: TumbleTrak Punch over obstacle
- Flip Training III: Free Flipping TTrak to Resi
Of note, coach felt punch still could be improved. Spent the beginning of the session working on the developing the punch Body control appeared to have improved. When harnessed into the trampoline flip apparatus, participant also appeared to have difficulty punching and gaining initial rotation, often stopping midway through the motion. Coach alternated Dive Roll Training II and Flip Simulation II to improve punch and integrate it towards the flip. Once consistent, took to tumble trak for Dive Roll Training II. Gradually raised height of obstacle until virtually performing flips. Spotted full flips on TTrak.

Post Trial From Questionaire, Participant 5 rated their overall feeling from the day as 5 out of 5, control over their actions as 5 out of 5, level of fear they experienced as 3 out of 5, and confidence in their ability to perform actions as 4 out of 5.

Reviewer’s mental model score for their understanding of the front flip was 2.33 out of 4 with a std deviation of 0.57. Reviewer’s average performance judgement score was 5 out of 8, with a std deviation of 1.69.

Commentary I tried to do a dive roll, but in the end my hands didn’t touch the mat, and that was the front flip! I was wearing the safety belt, but for a few times I couldn’t front flip and just ended up landing weirdly, that wasn’t great I need momentum from the trampoline, and enough heigh to go forward. I need to aim my hands far, and when I land I need to make sure my knees are apart so I don’t hurt my face. I need to aim my hands far when I jump, and when I land I need to keep my knees apart. Punching my feet hard in the trampoline! Holding my knees apart I wasn’t very confident because I was feeling sore from yesterday’s learning and was afraid I couldn’t do it. But it ended up fine! I feel very confident right now! I like the feeling of front flipping, being in the air. It was exciting.

8.7.5.4 Session 4

Pre-Trial Participant 5 arrived on time. They had 7 hours of sleep the night before. They experienced no stress.

Training Procedures Following the training procedure outlined by Phase II-Phase III, they worked through a progression from dive roll to front flip. They were randomly chosen to wear the AUFLIP feedback device.

- Warmup Stretch
- Flip Simulation I: Springboard to Elevated Surface
- Flip Simulation II: Trampoline with harness for complete spotted flip.
- Dive Roll Training II: Springboard Punch to Incline
- Dive Roll Training III: TumbleTrak Punch over obstacle
• Flip Training III: Free Flipping TTTrak to Resi

• Augmented Flip Training I: Use of the AUFLIP Feedback Device for Flip Training. (see figure x for procedure)

Of Note, punching performance appeared more consistent and comfortable. In trampoline harness, coach gave less support, participant execute flips mostly by self and committed to the movement. The participant was warmed up to flipping from the tumbletrak up to the resi, before donning the AUFLIP Feedback device.

Post-Trial From Questionaire, Participant 5 rated their overall feeling from the day as 4 out of 5, control over their actions as 4 out of 5, level of fear they experienced as 2 out of 5, and confidence in their ability to perform actions as 2 out of 5.

Reviewer's mental model score for their understanding of the front flip was 3.66 out of 4 with a std deviation of 0.57. Reviewer's average performance judgement score was 6.16 out of 8, with a std deviation of 0.40.

Commentary I did a standing front flip! When I realized my hands were off the grand that felt really good. I couldn't do a tumble track + high mat front flip! That one was really hard. Also another time on a high mat I knocked my knee into my eye. For the running front flip, I run, gaining momentum to punch off a spring/trampoline through taking a far last step. I throw my arms far and out, and bend my knees to gain the rotation motion. I land like a potato. Turns out I could do a standing front flip too! Throwing my arms out and high, getting the height from the trampoline, gaining momentum in my hips to push the hips high and forward. Landing on my back :) I felt good, although this is earlier than my usual waking hours. I felt great after the session. The hour past really fast! Much much faster than the previous 3 sessions. Once I completed a flip, I would an auditory response and look at the band on my arm for the numbers. However, the numbers had no units or legends so I did not know what they meant until it was explained to me. It helped me understand how well I performed a flip and my elevation into the flip. The phone on my arm was easy to see and access. The one on my ankle bothered me a bit. I liked that I could control when the sensor took data. However, I think the sensor could be reset with a button on the phone rather than having to reach down and press the button on the board. Yes. It told me my elevation and whether I completed a flip If I completed a flip, the screen would read 100. Furthermore, it told me my takeoff speed which helped me know whether I need to work on my steps into the flip Yes it did. If I completed the flip, it displayed 100. If I didn’t it displayed 0. Plus, the auditory response would depending on my performance.
8.7.6 Participant 6

8.7.6.1 Session I
Safety falls forward rolls punch drills back and forth forward roll, forward roll, convert to dive roll. dive rolls higher and higher.
Data was lost of the first trial

8.7.6.2 Session II

8.8 Audio Movement Congruence Prototype Implementation

Figure 35: Audio Movement Congruence Implementation: Pure Data

The Puredata code functions by taking the input of the analog pins from the Arduino Uno and upon passing the input thresholds sends a bang to the following file openings where the sound files Grabbed.wav and Thunk2.wav are retrieved and then sent onward to readsf where they are sent to the earbuds represented by dac 1 2. The readsf also loops back into the open sound files to allow for a loop to occur but allows for the stop to appear as soon as a stop is sent by the down wave through the thresholds. The objects dac 27 and dac 28 were only present to display the input of the Arduino Uno for troubleshooting.


