Background and Motivation: We propose a high-risk and high-reward approach to movement rehabilitation that encourages safe physical risk-taking behaviors and allows individuals to better learn everyday movements that are affected in many clinical populations. Movement is an intricate process that most humans take for granted. Standing balance is a prime example as while it is seemingly simple, it involves diverse brain regions to maintain stability in an otherwise unstable mechanical system[1,2]. Theories and models for motor control help us understand the neurophysiological factors dictating *how* deficits in standing balance occur. However, it is the motor learning process that dictate *why* deficits occur, and the neurophysiological and behavioral factors influencing motor learning remain relatively unknown. Thus, understanding motor learning can transform rehabilitation interventions that address the cause (improving motor learning) rather than the effect (fixing motor control) of movement deficits. We propose a reinforcement learning paradigm to mathematically link behavioral risk-taking with exploration during motor learning of standing balance in pubescent adolescents with Developmental Coordination Disorder (DCD). This will be achieved with a unique human-in-the-loop robotic platform[3,4] that can alter the dynamics of natural standing balance to force motor learning in novel physical environments.

Motor Learning: To produce movement, the brain first has to learn which muscle actions generate which movement outputs[5]. The cerebellum has been implicated in this task by learning internal representations of the body that are used to predict movement outcomes from motor commands[6]. Most motor learning is thought to occur during childhood and adolescence, during which adjustments to internal representations are needed to adapt to a constantly growing body and a still developing brain[7]. Broadly speaking, motor learning concepts can be divided into two paradigms: model-based and model-less[8]. Model-based learning defines internal representations of the body as physical models (e.g. inverted pendulum as a physical model of standing balance) to predict what movements the muscles produce based on physical laws[6,9]. Model-less learning, which includes reinforcement learning, defines internal representations of the body as mapped associations between muscle actions and movement outputs[10].

Exploration through Risk Taking: The distinction between motor learning paradigms is important as they are differentially affected by motor error: differences between the desired motor command and actual muscle output. Motor error in the model-based learning paradigm is detrimental because it prevents accurate predictions of desired movements[11,12]. However, motor error has been experimentally identified as beneficial because it encourages exploration of muscle action and movement output associations to discover a desired movement[10]. This idea of exploration is unique to the model-less learning paradigm and is balanced against exploitation of already mapped associations[10,13]. While exploration is necessary to discover new movement strategies, the brain is putting the body at risk. For standing balance, a naturally unstable task, excessive movement exploration could lead to a fall and subsequent injury.

Benefits of Behavioral Risk-Taking in Adolescents: Despite the potential for physical harm, literature from Collaborator Mariana Brussoni suggests that risk-taking behaviors during play can improve both motor learning and behavioral outcomes for children[14,15]. This contrasts with societal trends preferring risk-aversion in child care that have accelerated over the past several decades[16,17]. Risk-taking in play is thought to have an evolutionary basis as other species exhibit similar risky play behaviors[18], and stifling risk-taking may be disrupting physical learning in children[19]. Indeed, recent evidence suggests risk-aversion trends have led to profound consequences on child physical development[20].

Developmental Coordination Disorder: Cross-disciplinary observations from neurophysiology, behavioral psychology, and education highlight the benefits of risk-taking in motor learning, but there remains a translational gap. Pubescent adolescents (aged 11-16) with DCD serve as an ideal clinical population to study and apply these converging concepts. Adolescents undergo substantial physical and neurological changes necessitating relatively rapid motor learning and exhibit behavioral changes including increased risk-taking behaviors[21]. DCD is a neurodevelopmental disorder characterized by poor motor coordination and "clumsiness" in movement tasks including upright standing balance affecting an estimated 400,000 school-aged children (<18) in Canada alone[22–25]. While the etiology of DCD is not well understood, current theories implicate deficits in the learned cerebellar internal representations of the body[26,27]. Findings from Co-A Jill Zwicker suggest that children with DCD have smaller cerebellar volume and under-activate the cerebellum during motor learning tasks[28,29]. While these studies have implicated deficits in the internal representation of the body[27], few have explored how these deficient representations are learned[30]. This is driven by diagnostic practices which focus on observations of the movement through assessments such as the Bruininks-Oseretsky Test of Motor Proficiency (BOT-2)[31]. Thus, while observational assessments focus on diagnosing DCD based on its manifestation, modeling the motor learning process will allow us to uncover *why* DCD occurs and provide effective rehabilitation interventions.

Objective: To transform physical rehabilitation by encouraging safe risk-taking behaviors to better learn motor tasks. This will be achieved in four hypotheses that link behavioral risk-taking with exploration during motor learning in standing balance for pubescent adolescents with DCD. **(H1)** The brain employs a model-less motor learning approach for the control of standing balance. **(H2)** Typically developing (TD) adolescents learn new motor tasks faster than adolescents with DCD. **(H3)** Slower learning in adolescents with DCD is due to greater risk aversion which limits exploration in the model-less paradigm. **(H4)** Motor learning in adolescents with DCD can be improved by encouraging them to safely take movement risks which induces exploration in the model-less motor learning paradigm.

Feasibility: To distinguish between the two motor learning paradigms in standing balance and relate motor learning to behavioral risk-taking, we will use a unique human-in-the-loop robotic platform[3,4] developed by Co-A Jean-Sébastien Blouin to alter the natural dynamics of the human body and compare motor learning in TD adolescents and adolescents with DCD. This decouples motor control, which in the model-based paradigm assumes natural inverted pendulum human body dynamics, from motor learning, which adapts to and accounts for unnatural dynamics, an advantage over external perturbation methods.

We will recruit 30 pubescent adolescents diagnosed with DCD (ages 11-16, 15 male and 15 female) and 30 age- and sex-matched TD adolescent controls mirroring sample sizes in other DCD motor coordination studies[30]. Adolescents will be recruited from Co-A Jill Zwicker's clinical database of over 800 children and adolescents with DCD. All adolescents will report their growth (height and weight) over the previous year to ensure consistency with pubescent changes[32]. We will then take measurements of their current height and weight as well as ask for their sex at birth and gender classification according to Statistics Canada definitions[33]. Baseline measures of risk-taking behaviors and motor performance will be collected using the self-reported Domain-Specific Risk-Taking (DOSPERT) scale[34,35] and BOT-2[31] respectively. DOSPERT separates risk-taking into five content domains and has been validated in both adolescents and adults[35–37], while BOT-2 assesses four motor area composites as a clinical assessment tool for adolescents with DCD[38]. We will have adolescents balance unassisted for three minutes and obtain the mean (neutral posture) and the minimum-to-maximum (sway range) body angle measured by the robotic platform[39,40]. Surface electromyography (EMG) of the tibialis anterior, soleus, and medial gastrocnemius will be collected to characterize EMG variability and magnitude[40–42].

Our unique robotic human-in-the-loop balance platform[4,42–47] measures torque inputs at the feet and moves the body according to natural or unnatural dynamics (Figure 1). Adolescents will balance on the robotic platform for one minute to familiarize with the system followed by 15 balance trials each lasting three minutes (sufficient for adults to adapt to altered torque offsets in pilot work)[4]. Trials will randomly alternate between three conditions (5 trials each): natural inverted pendulum dynamics, unnatural

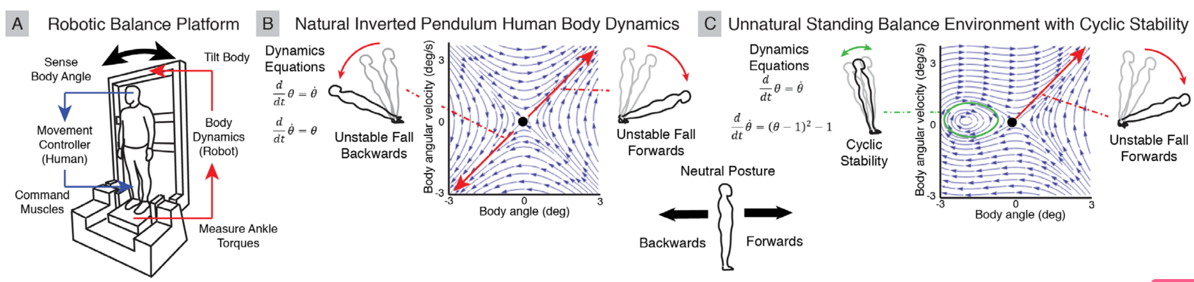

Figure 1: (A) Robotic balance platforms allow us to alter the body's (B) normally unstable inverted pendulum dynamics. Adolescents will learn to balance in (C) unnatural dynamics environments where a cyclic stability (stable oscillation) exists outside the normal sway range either in a forward lean or a backwards lean (backwards lean shown). The cyclic stability requires no effort to remain standing when leaning forwards or backwards, a posture that normally elicits balance-correcting responses.

dynamics with a forward lean cyclic stability, and unnatural dynamics with a backward lean cyclic stability. For each trial, adolescents will start at their neutral posture and we will quantify average body angle, sway range, EMG variability, and EMG magnitude over 10 second windows (0.1Hz resolution)[4].

H1: We expect that under the model-based learning paradigm, adolescents will balance where the body dynamics resemble the expected inverted pendulum (neutral posture) whereas under the model-less learning paradigm, adolescents will learn new motor-movement associations and balance in the cyclic stability (lean forward or backward) during unnatural dynamics trials. We also expect minimal EMG (effort) when balancing in the cyclic stability[48,49] that is not the normal model-based motor response.

H2: We will compare the time it takes for TD adolescents and adolescents with DCD to identify and balance around the cyclic stability in unnatural dynamics trials. This will be quantified within unnatural dynamics trials by computing the time to the first 10-second window in which body angle is within the cyclic stability boundary and EMG magnitude is below EMG activity that is measured in natural balance dynamics at the same body angle.

H3: To relate behavioral risk-taking to the mechanism underlying the difference in motor learning capabilities, we will correlate DOSPERT scores with the time in which TD adolescents and adolescents with DCD learn to balance within the unnatural dynamics trials. We also expect adolescents with greater risk tolerance will exhibit larger EMG variability and sway range at the beginning of each trial as a manifestation of the risky exploration process.

H4: we will repeat all 15 trials in the adolescents with DCD and encourage them to take motor risks in the first 30 seconds by instructing them to intentionally sway over the whole balance space. While normally there would be a risk of falling during large sways, the robotic platform can prevent this and safely allow for risk-taking. We expect that adolescents with DCD will learn to balance around the cyclic stability faster (with TD adolescent learning rate serving as the baseline) since the increased risk-taking behavior will augment the exploration process.

All analyses will be sex-stratified, as motor learning and brain neurophysiology are differentially affected by sex hormones that begin in adolescence and continue into adulthood[50]. Previous sex-dependencies specifically in standing balance have also been implicated in adults[51,52] and DCD is more common in males[53]. We will also collect gender information for exploratory analyses as there is a known relationship with behavioral risk-taking[21].

Timeline of Work:

Task	Year 1				Year 2			
Ethics Approval								
Trainee Hiring								
Programming Robot								
Setup DOSPERT + BOT-2								
Data Collection								
Data Analysis								
Knowledge Dissemination								

<u>Interdisciplinary Research:</u> This proposal brings together researchers from Engineering, Kinesiology, Rehabilitation, Pediatrics, Psychology, and Public Health with the mathematical expertise in reinforcement learning (PI Kuo, Collaborator Madhav), neurophysiological expertise in sensorimotor control (Co-A Blouin), psychological and public health expertise in risk-taking behaviors (Collaborator Brussoni), and clinical expertise in DCD (Co-A Zwicker) necessary to address the proposed study. Motor learning is an important skill at every stage in life and drastically affects independence and quality of life. Our team is utilizing mathematical models to link behavioral risk-taking with motor learning deficits in a clinical population (adolescents with DCD) leading to transformations in rehabilitation that can be applied across clinical populations. The New Frontiers in Research Fund mechanism provides the most suitable opportunity for our interdisciplinary high-risk, high-reward proposal, allowing us to transcend boundaries that typically silo basic science (NSERC), social sciences (SSHRC), and clinical applications (CIHR).

<u>High Risk:</u> Multiple evidence is converging on the concept that encouraging risky physical behaviors can enhance motor learning through an increase in exploration. We are proposing to unite findings from our multiple disciplines to mechanistically improve motor learning in rehabilitation through risky behavior.

<u>Unique Directions:</u> Our proposed study is challenging established movement rehabilitation methods which primarily involve practicing specific movement tasks[53,54]. By addressing **H4**, we are proposing that

to improve motor learning and motor coordination, rehabilitation should not restrict movement to repetitive practice of a single movement, but instead safely encourage individuals to take greater physical risks and explore the bounds of their motor capabilities.

Enhancing Understanding: This is predicated on our fundamental understanding of the motor learning process and how risk-taking behaviors can be represented as an exploratory process in the model-less reinforcement learning paradigm. While improving exploration of the sensorimotor space has been studied before[10,54], our work is tying this motor learning concept to a tangible behavioral metric (risk-taking) that can be communicated and quantified clinically (DOSPERT).

Development of Methods and Techniques: Indeed, we are proposing a new method to apply behavioral manipulations to induce predictable changes in motor learning. Traditional sensorimotor perturbations (applying sensory noise or external physical perturbations) to improve exploration can be better controlled but are fundamentally extrinsic manipulations that require continuous input to affect the desired changes in motor learning. Encouraging behavior changes (risk aversion vs. risk tolerance), while less precise, offers a novel intrinsic mechanism to induce beneficial long-term changes to motor learning.

Novel Interdisciplinary Approaches: Our proposal seeks to develop mathematical models (reinforcement learning) to link psychosocial behaviors (risk-taking) with neurophysiological observations (sensorimotor adaptation) to address clinical problems (DCD). Thus, our team requires expertise from these fields to contribute independent engineering, clinical, and behavioral observations on the mechanism of motor learning, health consequences of deficient motor learning, and psychosocial factors that contribute to improved motor learning respectively.

High Reward: Motor learning is a fundamental life-skill allowing humans to gain proficiency in performing tasks. Mechanistic understanding of the motor learning process can transform rehabilitation paradigms that will have a health impact on adolescents with DCD and populations requiring motor rehabilitation.

Transforming Conventional Thinking: DCD affects an estimated 400,000 school-aged children in Canada and is currently managed through occupational or physical therapy to better learn relevant motor skills[55,56]. While conventional methods aim to improve patient independence and life satisfaction by optimizing therapy according to patient needs, these methods still often target specific motor tasks themselves. Our proposed methods will radically transform rehabilitation in DCD to focus on improving the motor learning process, allowing for the acquisition of general motor skills. As DCD is a chronic life-long issue, addressing the root cause for DCD will reduce the healthcare burden and improve quality of life.

Impact on the Research Community: Our proposed study will introduce two novel elements to different areas of research that will lead to publications in high-impact, broad-interest journals such as the Journal of Neuroscience and Science Robotics respectively: 1) Strong evidence from education, public health, and psychological research have associated risky play to benefits in both neurocognitive and social development for children[14–16]. Our proposed reinforcement learning paradigm will formally quantify how risk-taking behaviors improve exploration and discovery in motor learning, which can be more broadly applied to other developmental aspects such as decision-making and socialization. 2) Our proposal utilizes a unique human-in-the-loop robotic standing balance platform to impose motor learning by changing the physical body dynamics[47]. While previous studies have applied external perturbations to induce motor learning, it remains unclear whether adaptations are resulting from updates to the internal representation or responses to the environment (external perturbation). Using human-in-the-loop control, we can decouple motor control from motor learning to illuminate their underlying mechanism and provide the necessary safe environment for risk-taking as the robotic standing balance platform will prevent falling.

Broad Health Impact: Similar motor coordination deficits also arise from acute injuries and chronic disorders at any stage in life. Stroke is one of the most common acute injuries that result in sensorimotor loss, with an estimated 62,000 people suffering a stroke annually in Canada[57]. Motor function recovery focuses on repetitive, context or task-specific movements[58,59], mirroring conventional practices for DCD. Improving motor learning in patients after stroke by making them comfortable with movement risks to explore the sensorimotor control space could provide similar benefits as in adolescents with DCD. Indeed, our findings could transform motor rehabilitation in occupational and physical therapy broadly, affecting a wide range of patients suffering from motor deficits resulting from injury, disease, or disorder.