

Smarter not Harder: Train the Brain Strategies to Optimize Your Athletes' Peak Performance

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Jennifer A. Hogg, PhD, ATC



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Disclosures

- Non-Provisional Patent Pending: Augmented and Virtual reality for Sport Performance and Injury Prevention Application filed 11/10/2016 (62/420,119), Software Copyrighted.
- Book Royalties
- Research Innovation funding
- Consultant for FDA Device applications to obtain US clearance

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Outline

- Detail the limitations with current Rehabilitation and Strength and Conditioning practice used for coaching for motor control and skill performance
- Review emergent technologies and their potential to support more central nervous system (CNS) and brain control of performance
- Discuss theoretical constructs that support a novel approach to coaching motor skills to optimize enhanced neuromuscular and sensorimotor control
- Evaluate the future potential of the integrated data fusion techniques supported by CNS and brain derived inputs for training injury prevention and performance enhancement

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THE PROBLEM



Immediate effects of Injury...



4

THE PROBLEM

Intermediate effects...

- Young Athletes subsequent ACL tear(s)
- Within 1 year after return to play,
 - 2nd ACL tear: ~30%

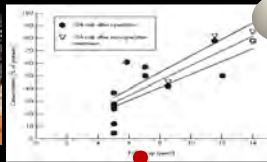


Wiggins 2016, Paterno AJSM 2010, Webster AJSM 2013, Paterno 2014

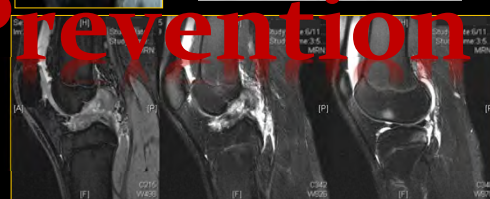
5

THE PROBLEM

...long term effects of injury



Prevention



Myklebust BJSM 2005

6

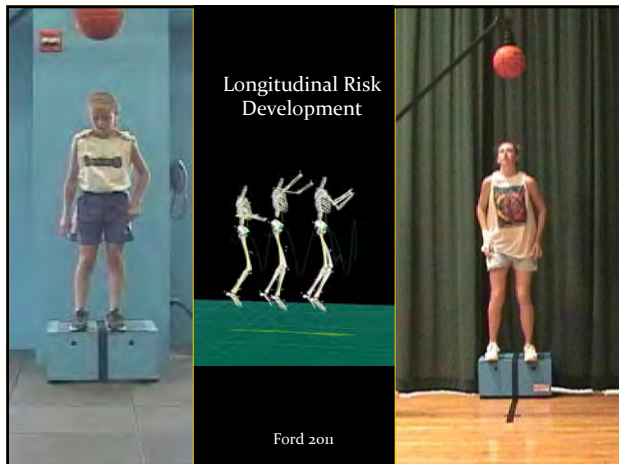
Can we even prevent knee injury?



Prevention 2000



7



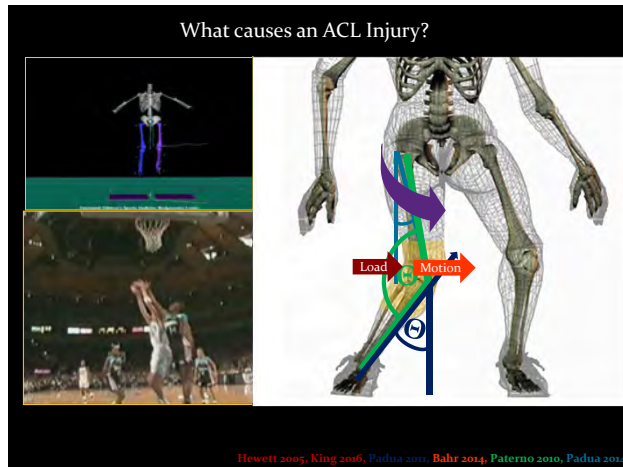
8

**Lack of Neuromuscular Spurt
Big Car-Small Engine?**



Hewett CJSM 2006

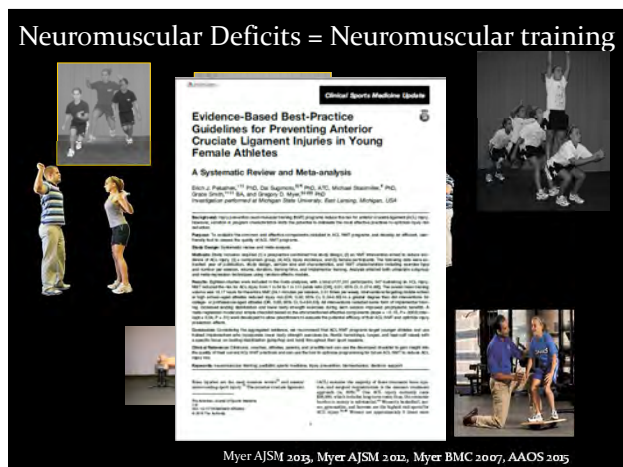
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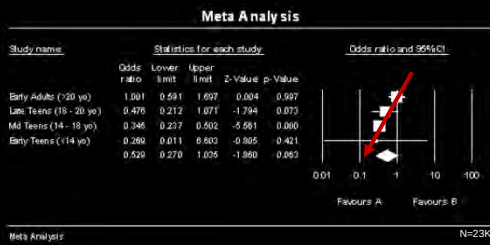


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Training young athletes works!

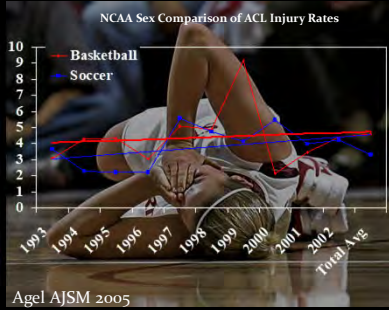


Myer 2015, Sugimoto 2016

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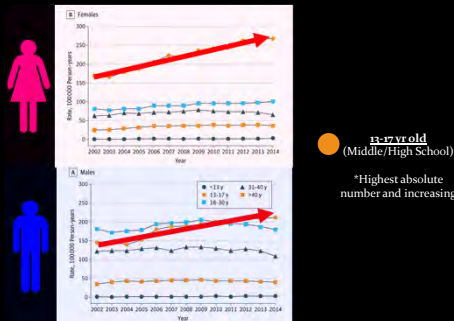
Why ↑ACL injury rate? ACL injury rate: ↑ 1.3% per year

Hootman JAT 2007



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Annual Trends in ACL Reconstruction



Herzog et al., 2017

Slide Stolen from Eric Petushek

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Dr. Neeraj Jayanthi

Study name	Statistics for each study				Odds ratio and 95% CI
	Odds ratio	Lower limit	Upper limit	p-value	
Hewett et al 1999	0.503	0.097	2.609	0.414	
Soderman et al 2000	0.510	0.578	48.779	0.140	
Heidt et al 2000	0.762	0.093	6.255	0.800	
Mykibust et al 2003	0.870	0.499	1.518	0.624	
Mandelbaum et al 2005	0.179	0.077	0.413	0.001	
Olsen et al 2005	0.318	0.086	1.181	0.087	
Petersen et al 2005	0.206	0.024	1.787	0.152	
Pfeiffer et al 2006	1.497	0.301	7.440	0.622	
Steffen et al 2008	0.705	0.189	2.633	0.603	
Ghlorhrist et al 2008	0.563	0.234	1.357	0.291	
Pasanen et al 2008	1.182	0.329	4.246	0.798	
Kiani et al 2010	0.085	0.005	1.535	0.095	
LaBella et al 2011	0.340	0.068	1.688	0.187	
Walden et al 2012	0.419	0.169	1.040	0.061	
	0.541	0.354	0.828	0.005	

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[illegible]

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Are Coaches able to **see** risk factors?



Dr. Joe Eisenmann, PhD

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Are Coaches able to **see** risk factors?



Eisenmann Family Pools

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Stages of Coaching/Instruction

- Deficits Identified
 - Targeted ID
- Cue Conceptualized
- Cue Articulated
 - Clear instructions?
- Cue Heard
- Cue interpreted
 - Correctly interpreted?
- Movement strategy conceptualized
- Internally Focused response

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Stages of Coaching/Instruction

Deficits Identified

Targeted ID



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Stages of Coaching/Instruction

Deficits Identified

Targeted ID

Cue Conceptualized

Which cue?

What driving deficits?

No magnitude quantification

Human Error-level of Expertise



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Stages of Coaching/Instruction

Deficits Identified

Targeted ID

Cue Conceptualized

Cue Articulated

Clear instructions?



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Stages of Coaching/Instruction

Deficits Identified

Targeted ID

Cue Conceptualized

Cue Articulated

Clear instructions?

Cue Heard

Listening?



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Stages of Coaching/Instruction

Deficits Identified

Targeted ID

Cue Conceptualized

Cue Articulated

Clear instructions?

Cue Heard

Cue interpreted

Correctly interpreted?



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Stages of Coaching/Instruction



Correctly interpreted?

Movement strategy conceptualization

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Stages of Coaching/Instruction

Deficits Identified



Movement strategy conceptualization
Internally Focused Strategy employed

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Stages of Coaching/Instruction



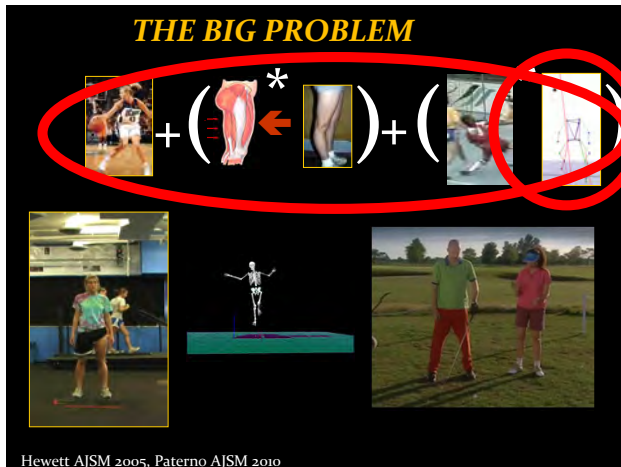
Even Movement Mimicry does not always transfer

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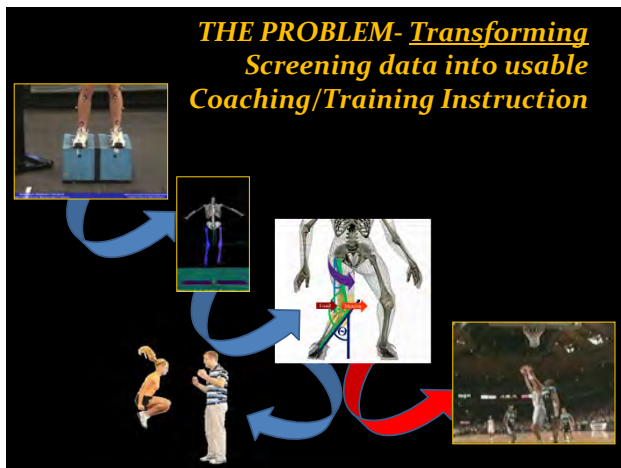
Adding to THE PROBLEM



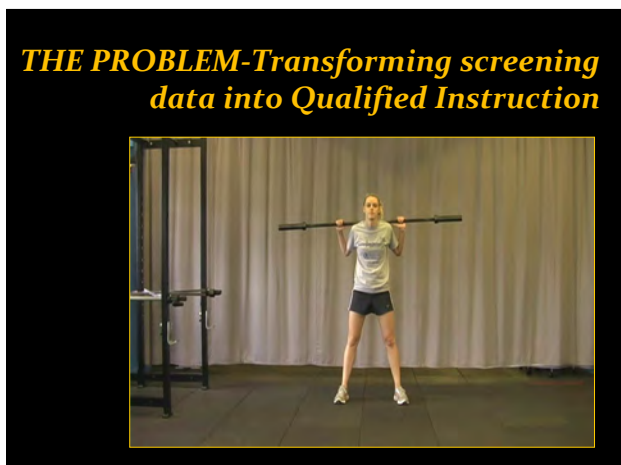
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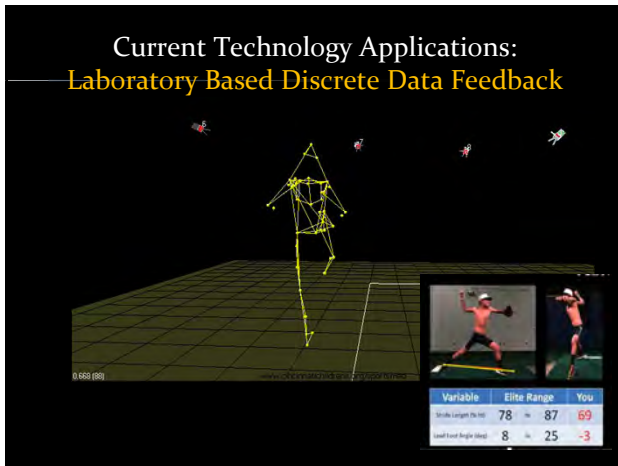
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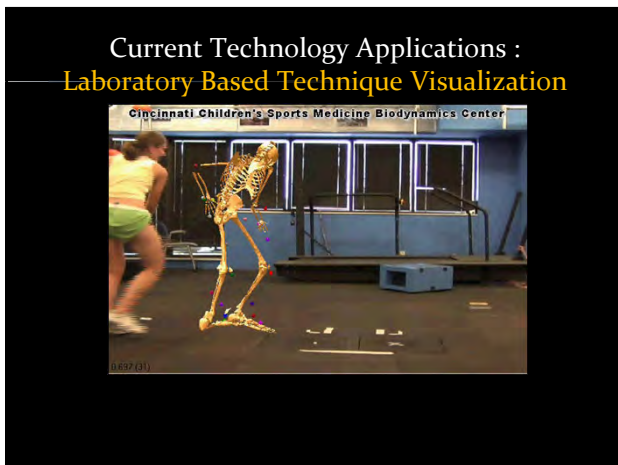
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Current Technology Applications: Laboratory Based Discrete Data Feedback



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Current Technology Applications : Laboratory Based Technique Visualization



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Current Technology Applications: Field based wearables



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Current Technology Applications: Field based wearables-GPS Watches and HR Monitors



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Current Technology Applications: Field based wearables-Pods



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What are we missing with these technologies?



Michael Biller, PT

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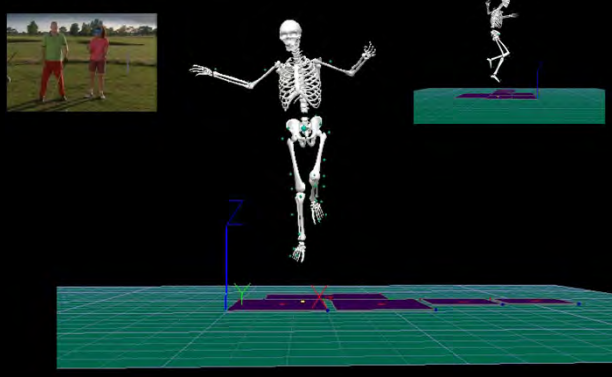
Is Real Time Biofeedback from Biomechanical Technology Possible?



Ford 2015

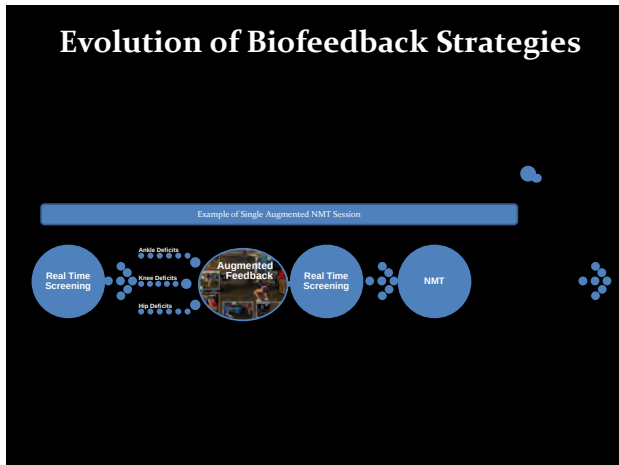
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But neuromuscular control deficits that underlie injury Risk more global in nature?

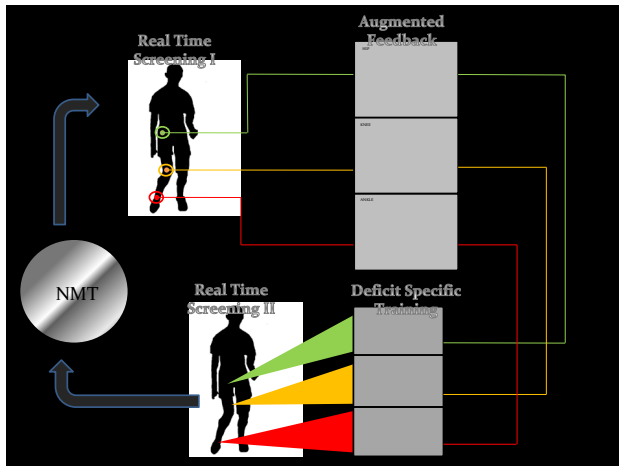


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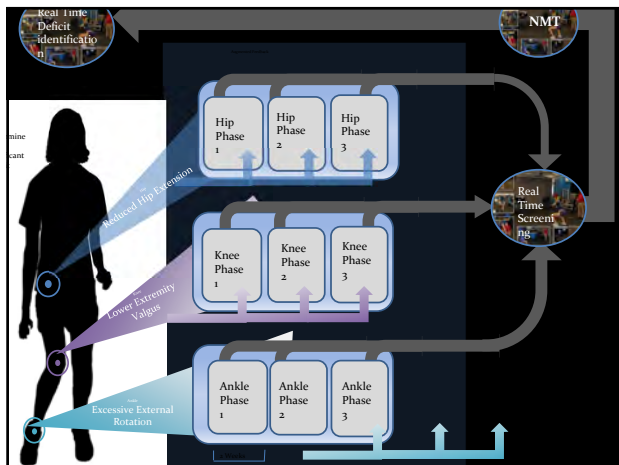
Evolution of Biofeedback Strategies



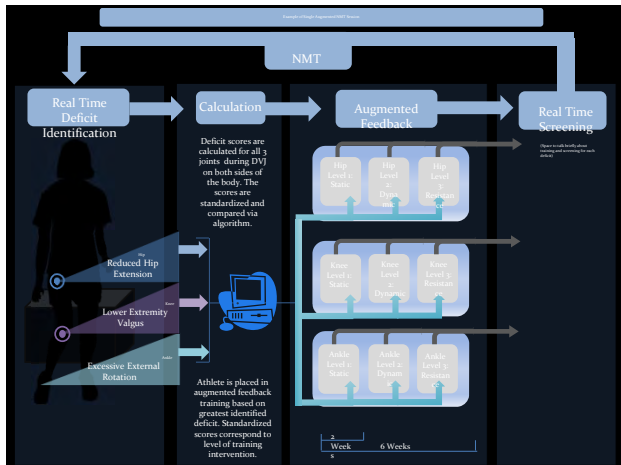
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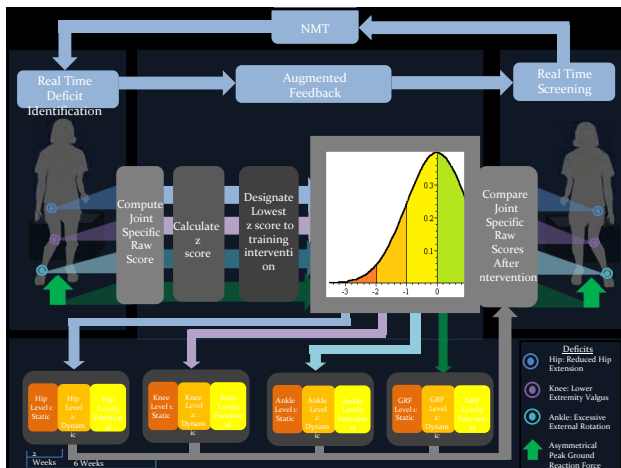
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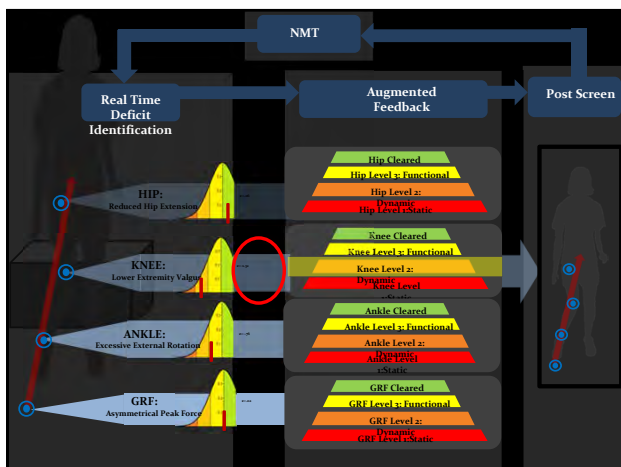
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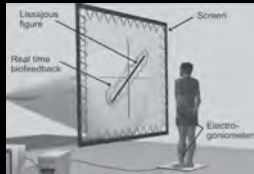
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Sensorimotor Learning: Feedback Mapping

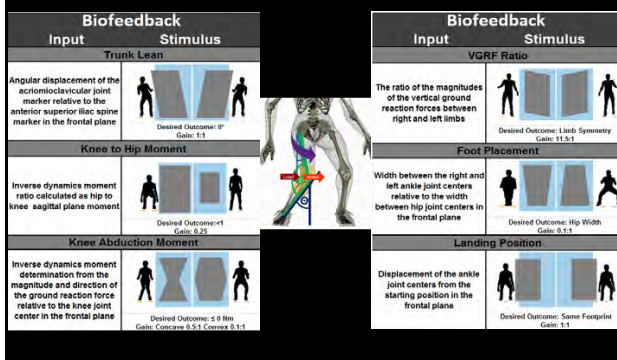
Faugloire et al. (2005)



- Subjects quickly learned hip-ankle coordination patterns by “drawing” diagonal lines (in-phase coordination) or circles (anti-phase coordination)
- Intervention for stroke patients resulted in long-lasting improvements in balance control

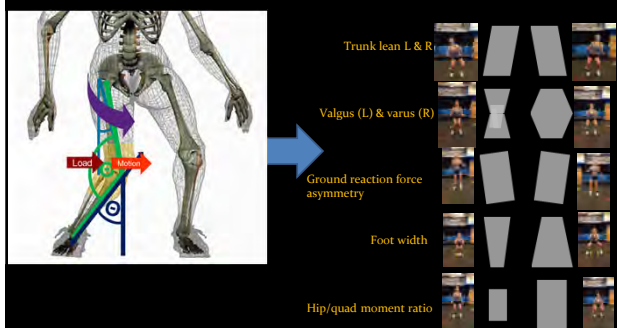
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Deconstructing the Biomechanics underlying bad training movement

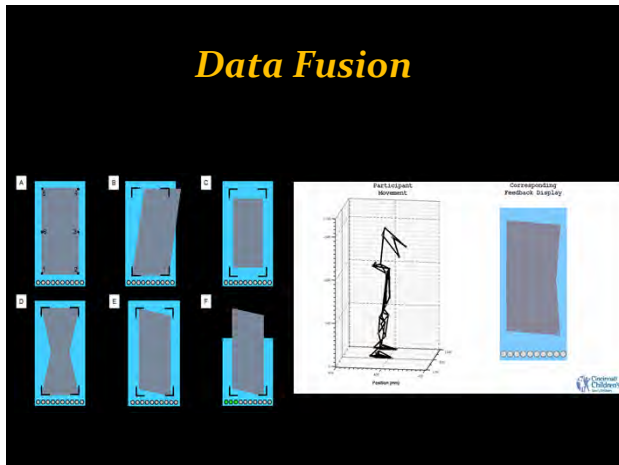


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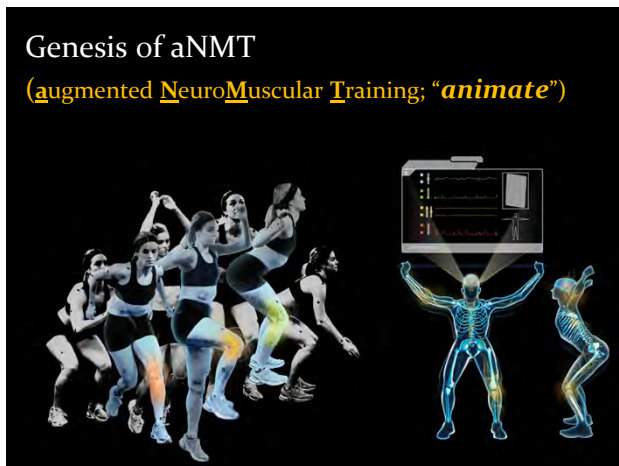
Mapping Deconstructed Biomechanics to real-time stimulus: Initial Prototypes



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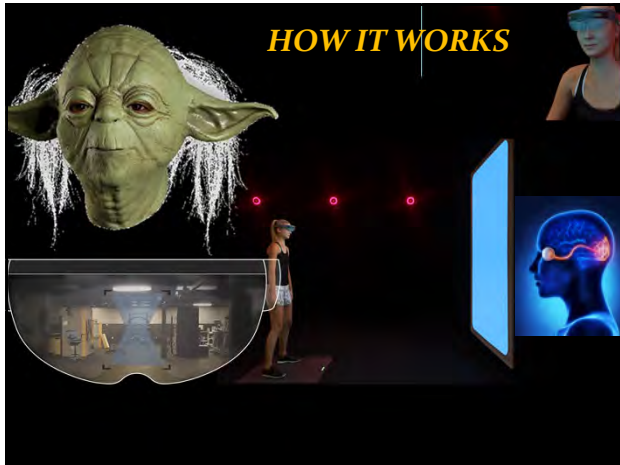
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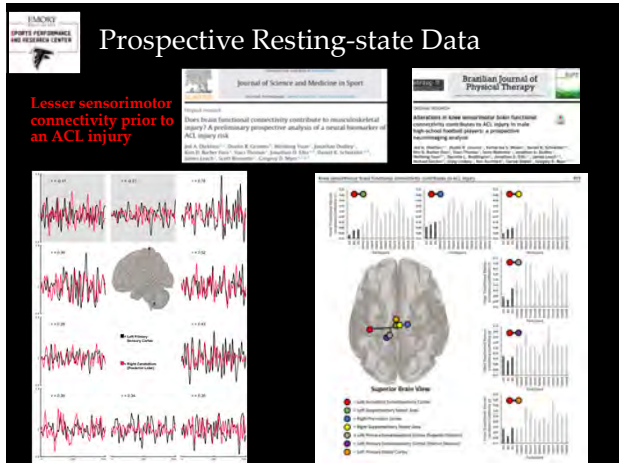
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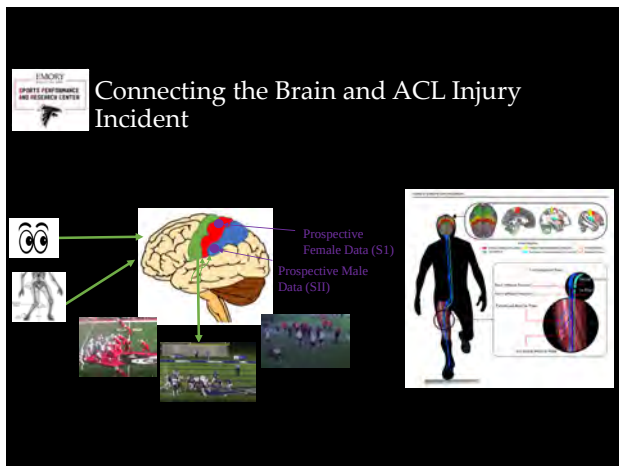
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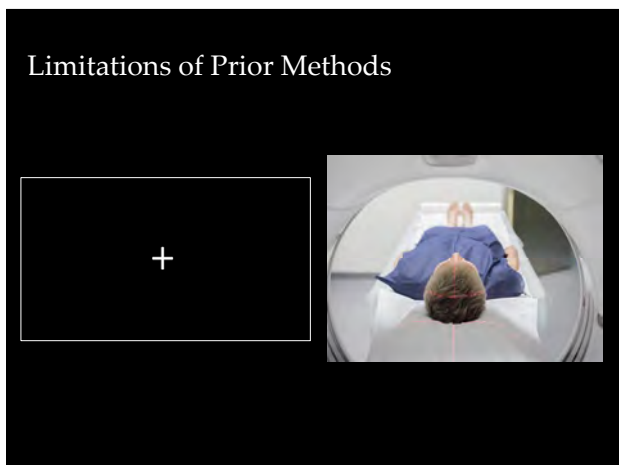
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Measuring the Brain and Motor Control



A Novel Approach to Evaluate Brain Activation for Lower Extremity Motor Control

Dustin R. Grooms¹, Jed A. Diekhaus², Jonathan D. Ellis³, Weihong Yuan⁴, Jonathan Duffley⁵, Kim D. Barber Foss⁶, Brian Thomas, Weidong Abala⁷, Larry Hays⁸, Brynne Williams⁹, John M. Lerner¹⁰, Kaley Bridgeman¹¹, Gregory D. Wyer¹²

From ¹Ohio Neuroscience & Neurological Institute and Division of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ²the SPORT Center Division of Sports Medicine, a Division of the Institute of Sports Medicine, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ³Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ⁴Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ⁵Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ⁶Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ⁷Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ⁸Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ⁹Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ¹⁰Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ¹¹Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA; ¹²Department of Molecular Biology, School of Applied Health Sciences and Medicine, College of Health Sciences, Ohio State University, 300 W. 17th Avenue, Columbus, Ohio 43210, USA

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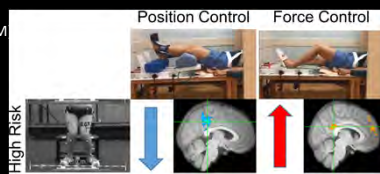
Neural Correlates of ACL Injury Risk

- Screened patients during DVJ:
 - high risk (increased KAM)
 - low risk (low KAM)

- Neuroimaging paradigms of:
 - Knee position control



- Knee force control

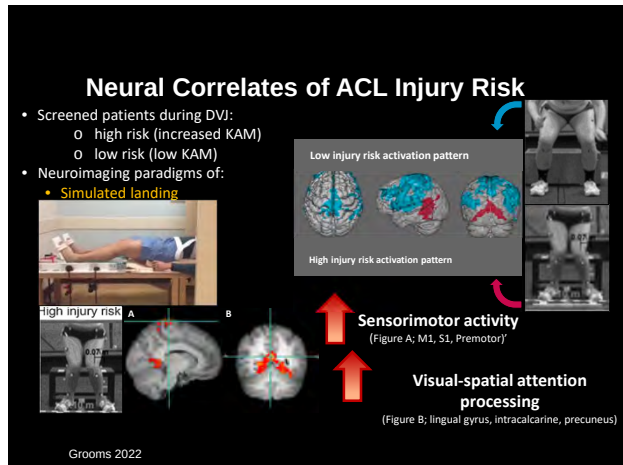


 **Sensory-cognitive**
(Posterior cingulate & Frontal cortex)

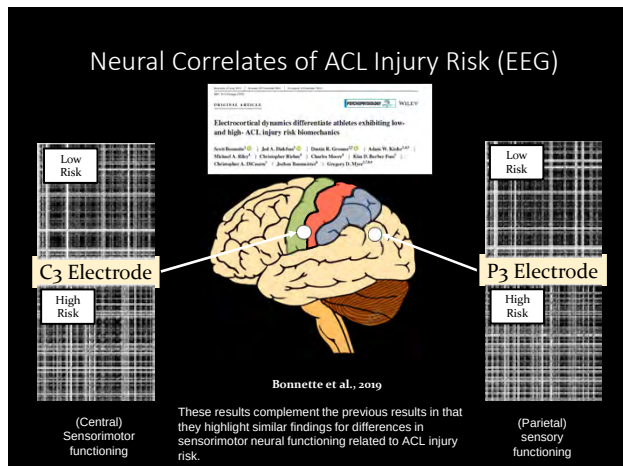
 **Sensory-motor**
(Precuneus)

Grooms JAT Part I 2022

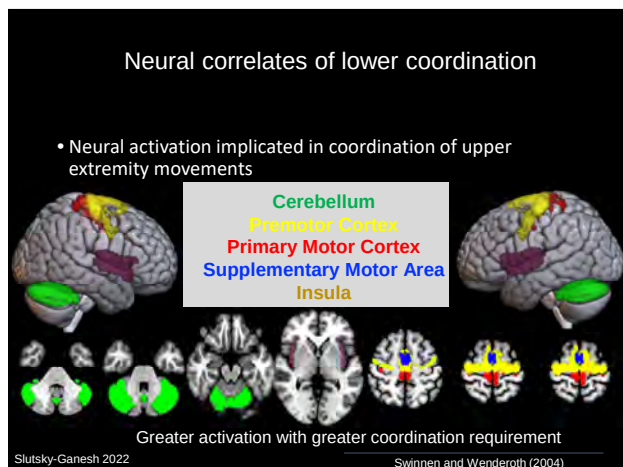
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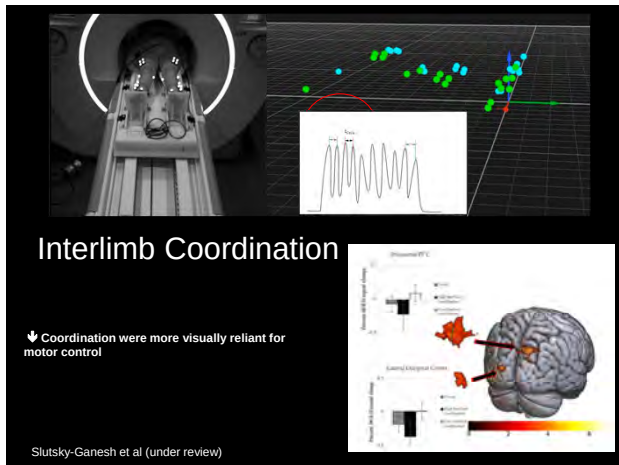
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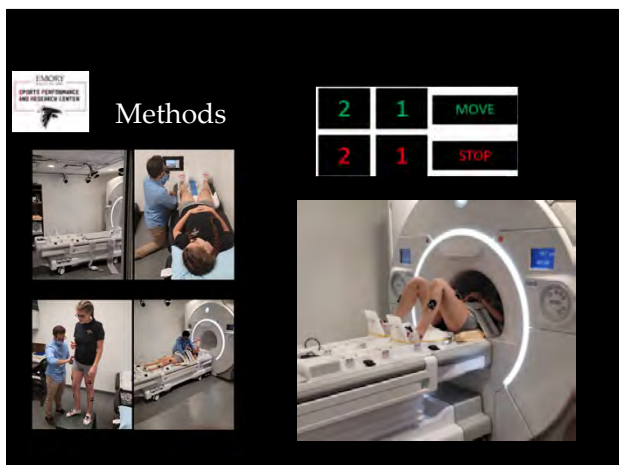
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Prospective Motor Data

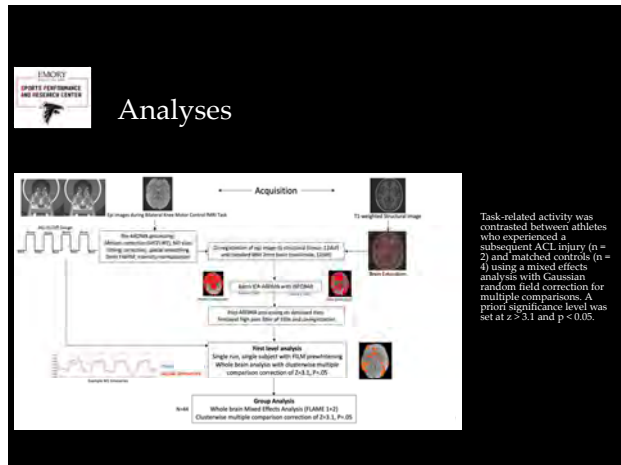
- 106 female middle and high school athletes who participated in soccer, basketball, and/or volleyball were evaluated using brain fMRI prior to their competitive sports season.
- Two athletes sustained an ACL injury (14.5 ± 0.7 years; 160.02 ± 1.79 cm; 55.5 ± 8.06 kg) during soccer activities.

ID	Age	Sport	Height	Weight	Hand	Foot
ACLInjured_1	15	Soccer	5'3.5	110	Right	Right
ACLInjured_2	14	Soccer	5'2.5	135	Right	Right
Healthy Control_1	15	Soccer	5'1	115	Right	Right
Healthy Control_2	15	Soccer	5'0	125	Right	Right
Healthy Control_3	14	Soccer	5'4.5	120	Right	Right
Healthy Control_4	13	Soccer	5'2	125	Right	Right

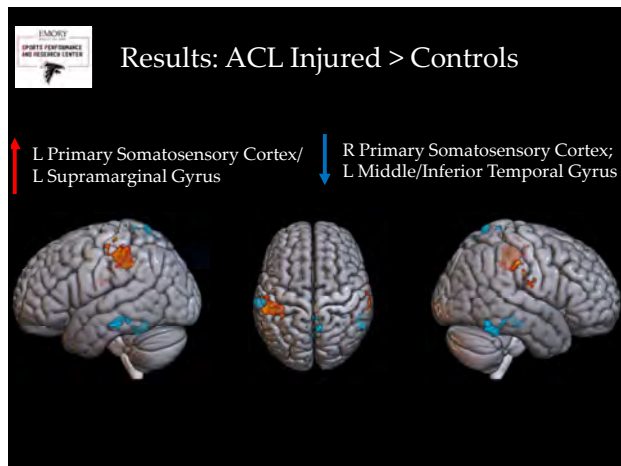
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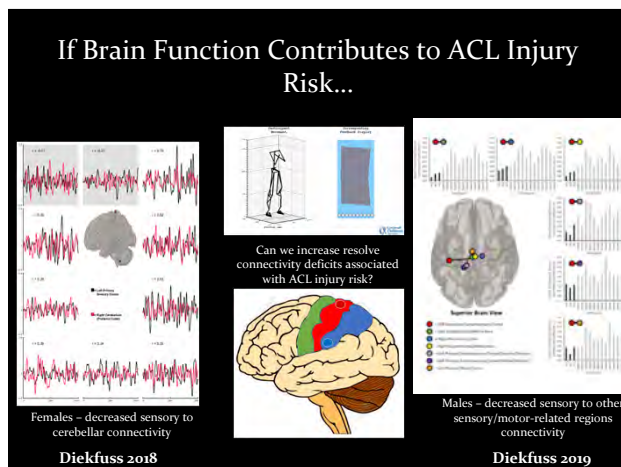
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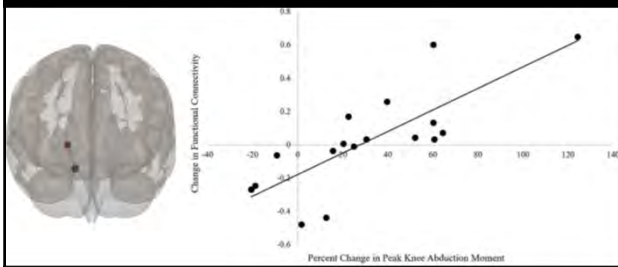


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Brain and biomechanical adaptations from aNMT

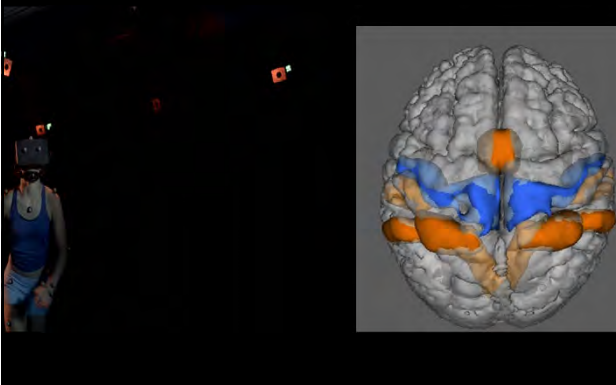


aNMT increased functional brain connectivity between the right supplementary motor area (SMA) and the left thalamus

Dickfuss 2019

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DOES aNMT INDUCE MORE CENTRAL ADAPTATIONS THAT SUPPORT ADAPTIVE TRANSFER TO THE FIELD OF PLAY?



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Potential Value of VR Testing

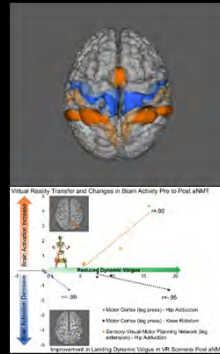


Dicesare 2019, Kiefer 2017

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aNMT to Train the Brain

- aNMT Increased sensory-visual-motor integration activity
 - Improved neural processing to control knee positioning during landing simulation
- aNMT increased transfer of injury resistant training adaptations to immersive sport scenarios
- Enhancing neuromuscular training with sensory, visual-spatial, and motor anticipatory exercises may further improve efficacy
 - Adaptive strategies to overcome functional neural connectivity deficits associate with ACL injury risk

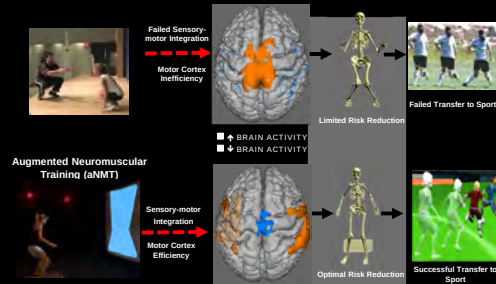


Grooms 2019

Grooms 2018

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Can we 'Train the Brain' and reduce ACL Injury Risk?



Grooms JAT Part II 2022

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YES

Preliminary Report on the Train the Brain Project: Neuroplasticity of Augmented Neuromuscular Training and Improved Injury Risk Biomechanics - Part II

Researcher: [Name] | Institution: [Institution] | Date: [Date] | Status: [Status] | URL: [URL]

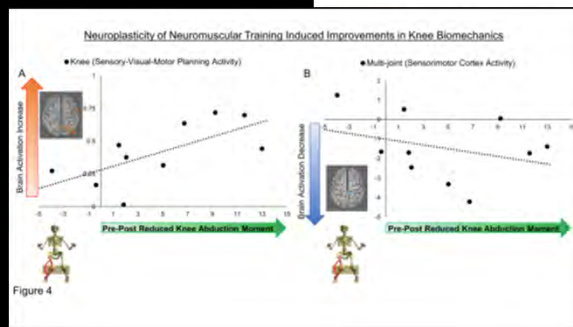
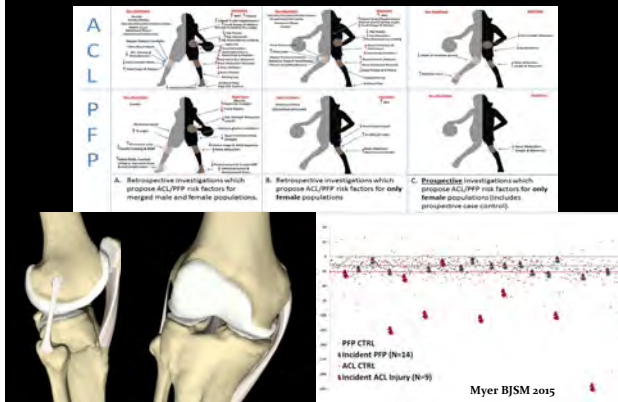


Figure 4

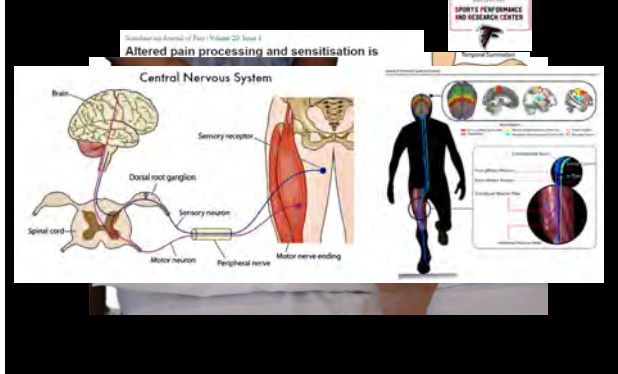
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What about something besides ACL Injury?



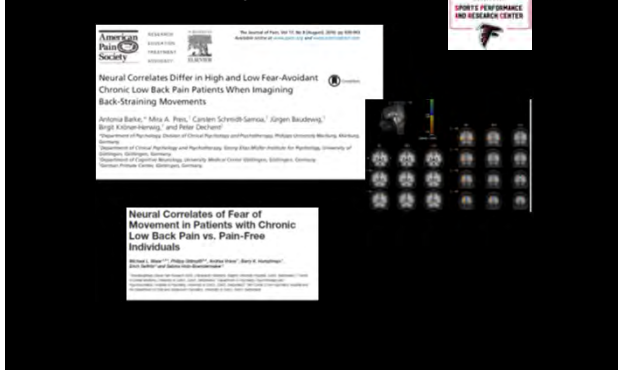
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Patellofemoral Pain



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CNS Plasticity



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Movement-Evoked

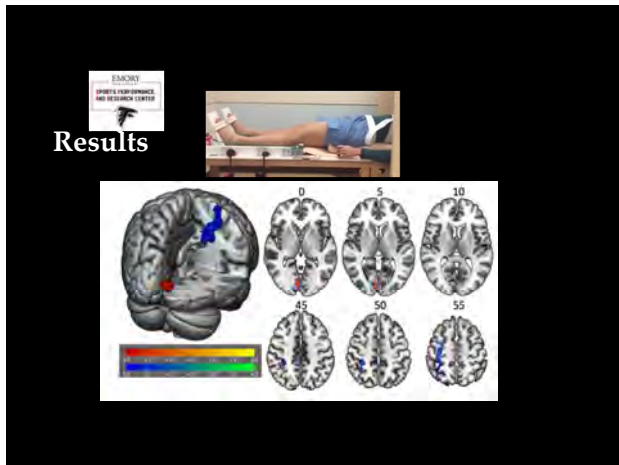
- Movement paradigm
- 4 sets – Block Design
 - Rest
 - 30 seconds
 - Knee Leg Press
 - 30 seconds
 - 1.2 Hz movement frequency (36 cycles)

Tasks are pain-inducing for patients with PFP

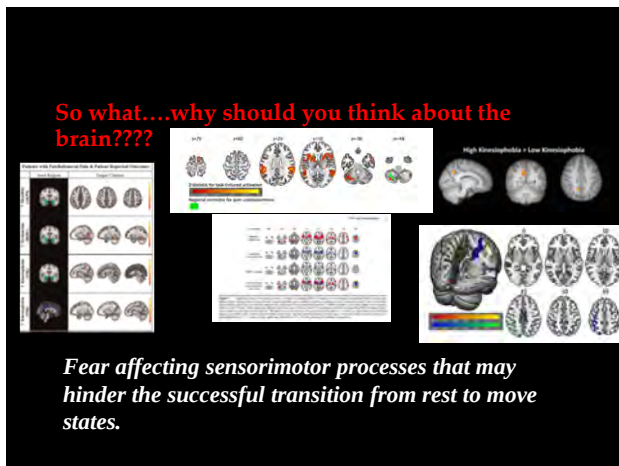
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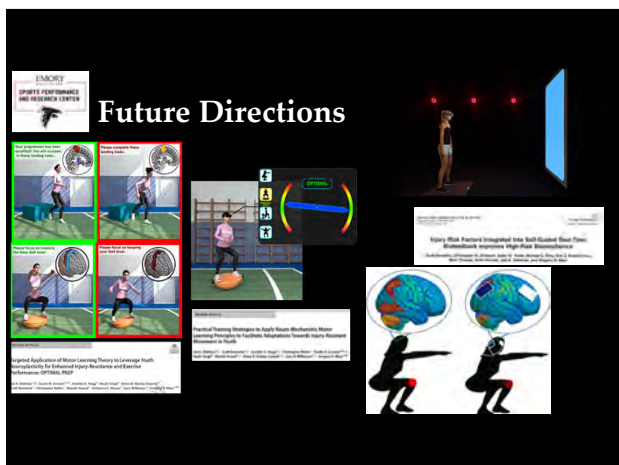
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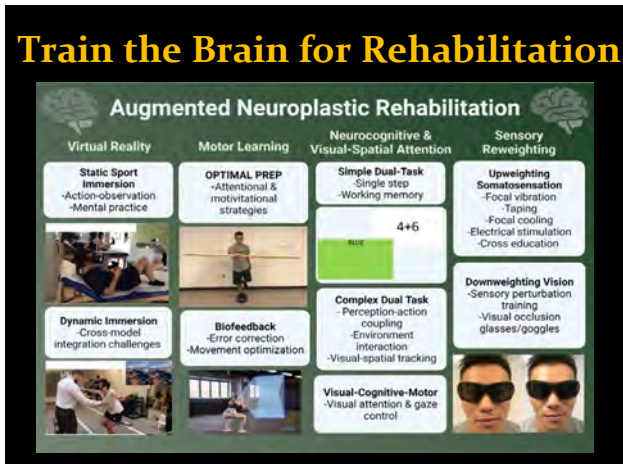
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Train the Brain for Rehabilitation: Four Targetable Neural Pathways

1. Support Amygdalar Functioning
2. Reallocate Attentional Resources
3. Leverage Dopamine
4. Promote Individual Differences)
(Personalize

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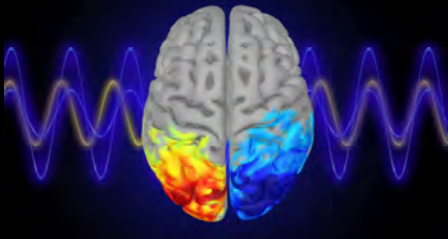
Train the Brain for Rehabilitation: Amygdalar Functioning



Diekfuss 2019

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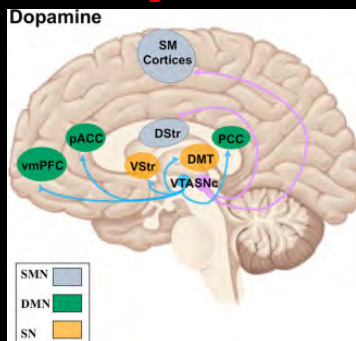
Train the Brain for Rehabilitation: Reallocation of Attention



Diekfuss 2019

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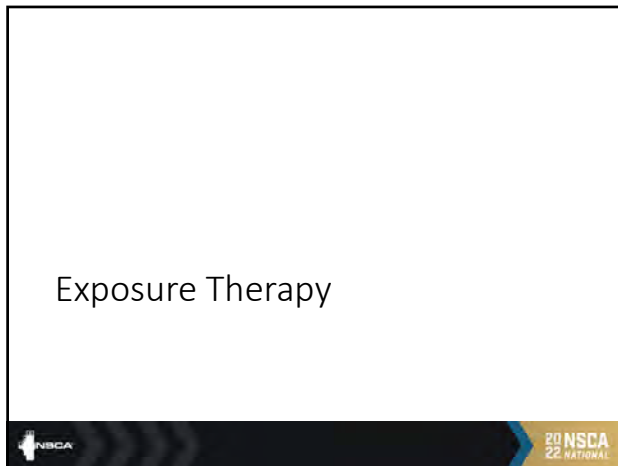
Train the Brain for Rehabilitation: Dopamine



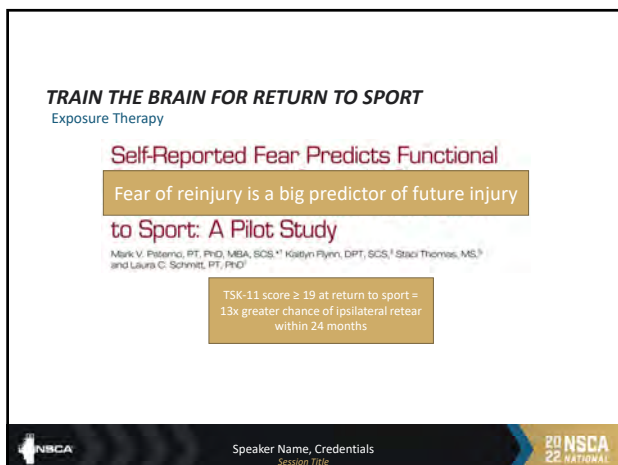
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TRAIN THE BRAIN FOR RETURN TO SPORT

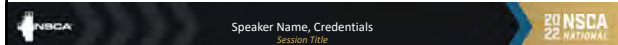
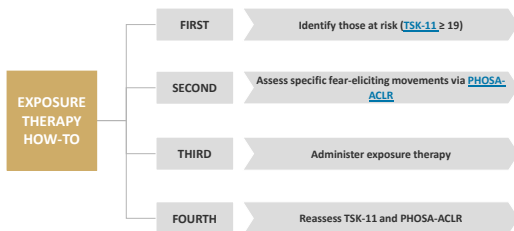
Exposure Therapy

Gradual exposure to fear-eliciting movements

Exposure therapy can address injury-related fear

Can aid patients with chronic low back pain (Baez, Hoch, & Hoch, 2018)

Can increase physical activity levels (Vlaeyen et al., 2002)



STEP 3—EXPOSURE THERAPY INTERVENTION

Table 1

Task	Progression 1	Progression 2	Progression 3	Progression 4
Running	Walk	Jog	Run	Run on Incline

1. Running

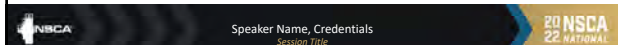
1. Running Score the activity depicted in the photograph below from 0 to 10, where 0 is "not harmful at all" and 10 is "extremely harmful".		eg Jump off 8 inch step eg Squat with No Weight	Double-Leg Jump off of 12 inch step Double-Leg Squat with Weight
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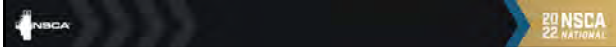
1. Demonstrate walking
2. Athlete rates walking 1-10
3. Athlete performs walking
4. Athlete re-rates walking
5. If improved, progress

0	1	2	3	4	5	6	7	8	9	10
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Baez et al., 2021, Phys Ther Sport



Dual-Tasking



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NEUROCOGNITION—IS IT IMPORTANT FOR MSK INJURY?

The Relationship Between Neurocognitive Function and Noncontact Anterior Cruciate Ligament Injuries

Charles Buz Swank,¹ PhD, ATC; Tracey Covassin,² PhD, ATC;
David J. Stearne,³ PhD, ATC; and Philip Schatz,⁴ PhD

Prospective association with injury occurrence

Visual-Spatial Attentional Performance Identifies Lower Extremity Injury Risk in Adolescent Athletes

Jason M. Avedisian, PhD,¹ April L. McPherson, PhD,¹ Jed A. Diekhuss, PhD,² Kim D. Barber Foss, MS, ATC, LAT,³ Jennifer A. Hogg, PhD, ATC,³ Taylor M. Zueger, BA, BS,⁴ Janet S. Dufek, PhD,¹ and Gregory D. Myer, PhD,⁵†††

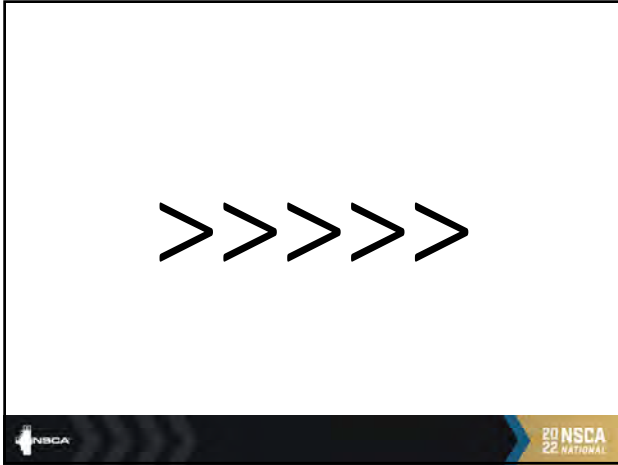


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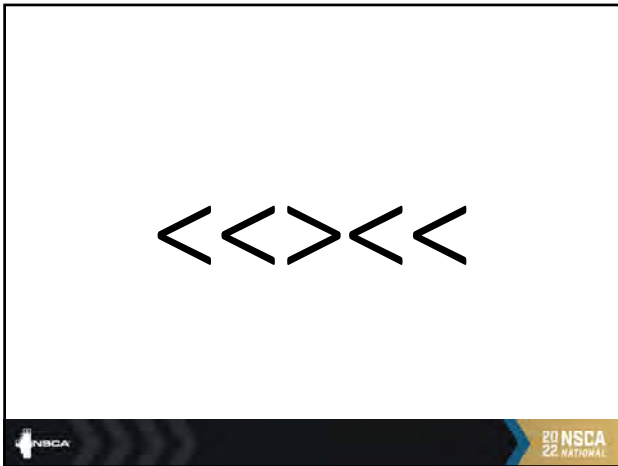
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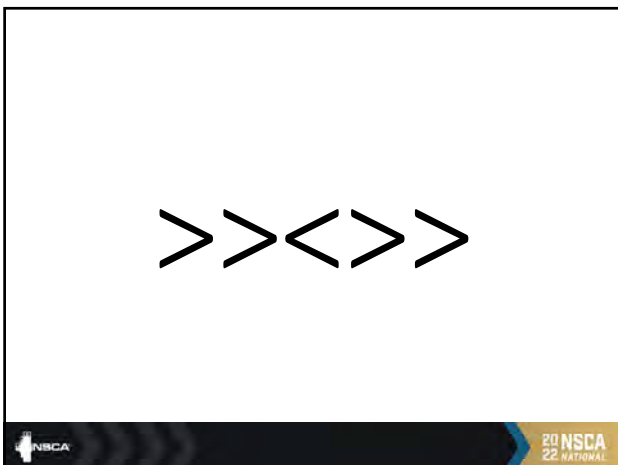
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NEUROCOGNITION AND LOWER EXTREMITY MECHANICS

Visual-Spatial Memory Deficits Are Related to Increased Knee Valgus Angle During a Sport-Specific Sidestep Cut

Scott M. Montfort,^{1,†} PhD, Jared J. Prisdavsky,¹ BS, Dustin R. Grooms,^{2†} PhD, ATC, Keith A. Hutchison,³ PhD, James A. Chaffin,^{4,††} PhD, ATC, and Aki M.W. Cheudens,^{1,††} PhD
¹—performed at The Ohio State University Wexner Medical Center

Baseline neurocognition in males associated with suboptimal squatting and cutting

Sex Moderates the Relationship between Perceptual-Motor Function and Single-Leg Squatting Mechanics

Jennifer A. Hogg^{1§}, Justin M. Avelosian^{1,††}, Joel A. Dickfus^{1,††}, Shelle N. Accetta², Ryker D. Shimmeln³, Elizabeth A. Kelley³, Deborah A. Kostrah³, Gregory D. Myer^{1,§§§} and Gary B. Wilkerson²

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DUAL-TASKING: WHAT IS IT?

Combining neurocognition and lower extremity mechanics

Simultaneous completion of two goal-oriented tasks

1 cognitive + 1 motor

Simple

- Serial 7s
- Go-no-go

Complex/choice

- Language based
- Visuo-spatial
- Discriminatory



Hogg et al., 2021, *J Clin Trans Res*

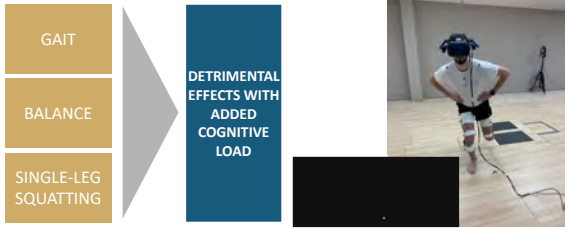
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DUAL-TASKING: THE EVIDENCE

During continuous tasks



Hogg et al., 2022, *J Strength Cond Res*; Williams et al., in press, *J Sport Rehab*; Burcal et al., 2019, *Sports Med*

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DUAL-TASKING: THE EVIDENCE
During discrete tasks

ATHLETIC MOVEMENT

Functional Sport Task

+ Cognitive Load

HIGH RISK BIOMECHANICS

Drop vertical jump
Side-step cutting

Serial 7s
Go-no-go
Unanticipated component

maximal jump height
knee flexion
GRF on landing

Lemple et al., 2021, J Sport Rehab;
Almonroeder et al., 2018, JOSPT; Dai et al., 2018, Sport Biomech

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HOW TO DUAL-TASK
On the field and in the clinic

Less Complex

More Complex

Word recall Simple math Go-no-go Stroop Visuo-spatial Discriminatory

Walker et al., 2021, Phys Ther Sport

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OPTIMAL PREP

Optimizing Performance Through Intrinsic Motivation and Attention for Learning:
Prevention Rehabilitation Exercise Play

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Session Title **NSCA 22 NATIONAL**

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OPTIMAL Theory

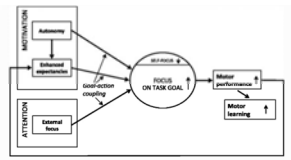
Framework

Motivational pillars

Autonomy support
Enhanced expectancies

Attentional pillar

External focus of attention

Wulf & Lewthwaite, 2016, *Psych Bull Rev*

OPTIMAL-PREP

Leveraging motor learning for improved movement

Moving away from goal-oriented movement and toward injury resistant movement (**P**revention, **R**ehabilitation, **E**xercise, **P**lay)

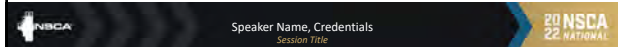
Targeted Application of Motor Learning Theory to Leverage Youth Neuroplasticity for Enhanced Injury Resilience and Exercise Performance: OPTIMAL POST

[illegible]

Can We Capitalize on Central Nervous System Plasticity in Young Athletes to Inoculate Against Injury?

Practical Training Strategies to Apply Neuro-Mechanistic Motor Learning Principles to Facilitate Adaptations Towards Injury-Resistant Movement in Youth

Diekfuss et al., 2020a & 2020b, *J Sci Sport Ex*; Diekfuss et al., 2021, *J Sci Sport Ex*



EXTERNAL FOCUS OF ATTENTION

Focusing on the effects of the movement

Improves:

Knee valgus during gait (Aghakeshizaden et al., 2021, *Gait Posture*)

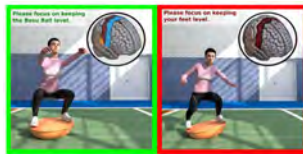
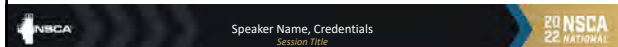
Knee flexion angles (Gokeler et al., 2015, *Phys Ther Sport*)

Muscle activation (Lohse et al., 2010, *Hum Mov Sci*)

LESS score (Welling et al., 2016, *Hum Mov Sci*)

Dual-task cost during single-leg balance

(Williams et al., in press, *J Sport Rehab*)

Diekfuss et al., 2021, *J Sci Sport Ex*

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EXTERNAL FOCUS OF ATTENTION

Ways to implement

- As simple as changing a few words
- Check compliance throughout
- Strive for 'task relevant' word choice
- Focus further away from body (Porter et al., 2012, *J Sport Cond Res*)

Table 3 Implementation of external focus of attention within existing ACL injury rehabilitation protocols

Existing therapeutic exercise	Category of external focus of attention	Implementation of external focus of attention
Forward and lateral lunges	Frequency	Additionally including verbal instructions that ask patients to extend past a piece of tape placed on the floor
Chamshell	Distance	Verbally instruct the patient to "Concentrate on reaching for the ceiling"
Gluteal bridging	Direction	Verbally instruct the patient to "Press the floor away"
Physometric training	Practice variability	Varying barriers, depths, directions, and bases of support

Diekfuss et al., 2020, *J Sci Sport Ex*



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AUTONOMY SUPPORT

Giving learners control over their environment

Improves:

Squatting mechanics (Hogg et al., ACL Research Retreat, 2022)

Balance (Wulf & Toole, 1999, *Res Quart Ex Sport*)

Golf putting task (McKay & Ste-Marie, 2020, *Hum Mov Sci*)



Diekfuss et al., 2021, *J Sci Sport Ex*



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AUTONOMY SUPPORT

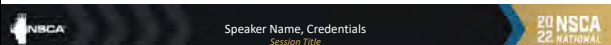
Ways to implement

- Task-irrelevant may be ineffective for highly motivated learners (Ikudome et al., 2019, *J Sport Ex Psych*)
- Can easily combine with enhanced expectancies, e.g. 'self-controlled'

Table 2 Implementation of autonomy support within existing ACL injury rehabilitation protocols

Existing therapeutic exercise	Category of autonomy support	Implementation of autonomy support
Hamstring curls	Task-relevant	Allow the patient to choose between the prone curl machine or ankle weights
Gait re-training	Task-relevant	Allow the patient to choose between a clockwise or counterclockwise walk around the clinic
Short-arc quadricep sets	Task-irrelevant	Allow the patient to choose the color of their bolster
Heel slides on wall	Task-irrelevant	Allow the patient to select the wall on which to perform heel slides

Diekfuss et al., 2020, *J Sci Sport Ex*



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ENHANCED EXPECTANCIES

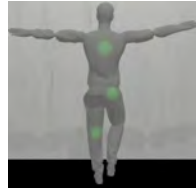
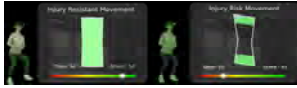
Enhancing the learners' expectation for success

Improves:

Squatting mechanics (Hogg et al., ACL Research Retreat, 2022)

BESS testing (Chua et al., 2020, *Gait Posture*)

Dual-task cost during single-leg stance (Williams et al., in press, *J Sport Rehab*)



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ENHANCED EXPECTANCIES

Ways to implement

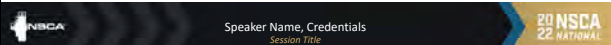
Can take many different forms



Table 1 Implementation of enhanced expectations within existing ACL injury rehabilitation protocols

Existing therapeutic exercise	Category of enhanced expectations	Implementation of enhanced expectations
Revision dead lift	Positive feedback	"You displayed excellent form during your previous set"
T-rod agility drill	Social-comparative feedback	"You completed your last repetition considerably faster than the average time for your sport"
Step-ups	Self-modeling	Provide edited video of previous repetitions deemed superior, emphasizing how such improvement has occurred
Single-leg balance	Perceived task difficulty	Initially redefine success and allow the opposing foot to touch-down, then progress to more challenging parameters, keeping pace with the patient's physical capability

Diekfuss et al., 2020, *J Sci Sport Ex*



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ADDITIVE EFFECTS?

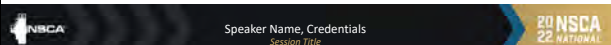


Combine multiple tenets in one statement
"Research shows that you perform better if you focus on keeping the BOSU platform level!"

Table 4 Implementation of additive effects within existing ACL injury rehabilitation protocols

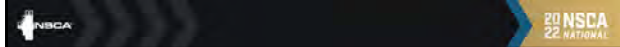
Rehabilitation Exercise	Enhanced expectations component	Autonomy support component	External focus of attention component
Standing hip abduction	"Your control and balance are much better than when you first performed this exercise"	Allow the patient to choose between performing this exercise at the beginning or the end of the rehabilitation session	Verbally instruct the patient to "Focus on extending towards the wall"
Single-leg squat	Emphasizing to the patient their improved endurance and ability to perform more repetitions accurately	Allow the patient to choose between performing 3 sets of 10 repetitions or 2 sets of 15 repetitions	Verbally instruct the patient to "Focus on pressing into the floor"

Diekfuss et al., 2021, *J Sci Sport Ex*; Chua et al., 2020, *Gait Posture*



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Personalization



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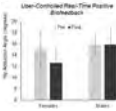
MALE V. FEMALE PERSONALIZATION

Different stimuli + different responses

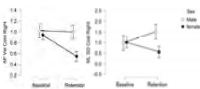
The anterior cruciate ligament injury controversy: is "valgus collapse" a sex-specific mechanism?

C.E. Quinlan, T.E. Hewett

Males with poorer baseline discriminative reaction time have greater pelvic drop.
Females with poorer baseline discriminative reaction time have greater valgus and trunk lean.

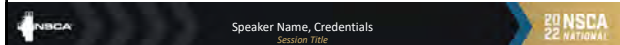


Females improved hip adduction during squatting after enhanced expectancies intervention



Females respond to external focus kinematic intervention as demonstrated by improved dual-task cost

Hogg, et al., 2022, J Sports Sci Med; Hogg et al., 2022, J Strength Cond Res; Hogg et al., 2022, ACL Research Retreat



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Session Title

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SEX-SPECIFIC TAKEAWAYS

Females respond to OPTIMAL PREP strategies targeting valgus mechanisms

Will males respond to similar strategies targeting sagittal plane mechanisms?

Or do males require a different stimulus? (e.g., dual tasking, leveraging vision)

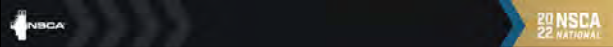


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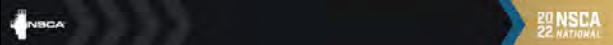
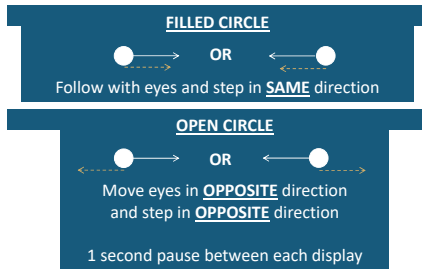
SO WHAT?

Scaling up

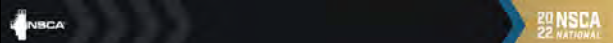
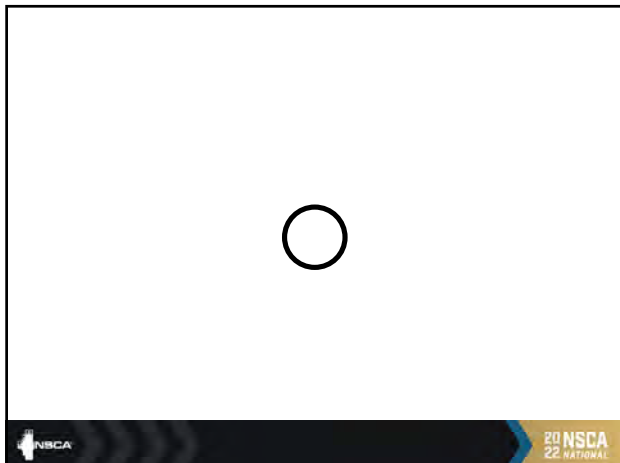
- Turnkey interventions
 - Independent of personnel
 - Independent of location
 - On demand
- Digital delivery methods
 - High end VR goggles (e.g., Oculus, HTC Vive)
 - Mid-shelf options (e.g., Kinect)
 - Low-tech options (e.g., Google Cardboard)



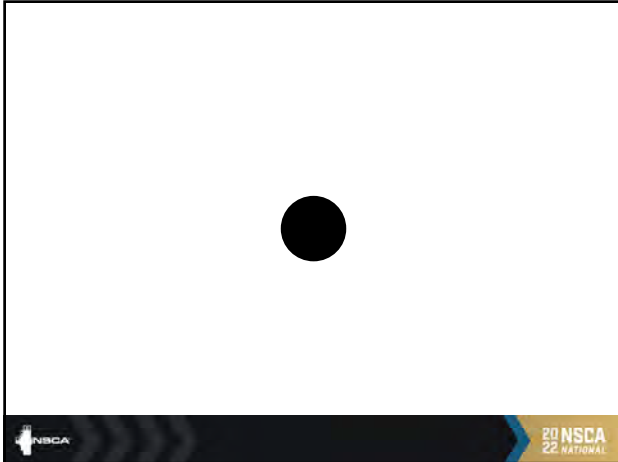
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EXAMPLE OF VISUO-SPATIAL DUAL-TASKING INTERVENTION

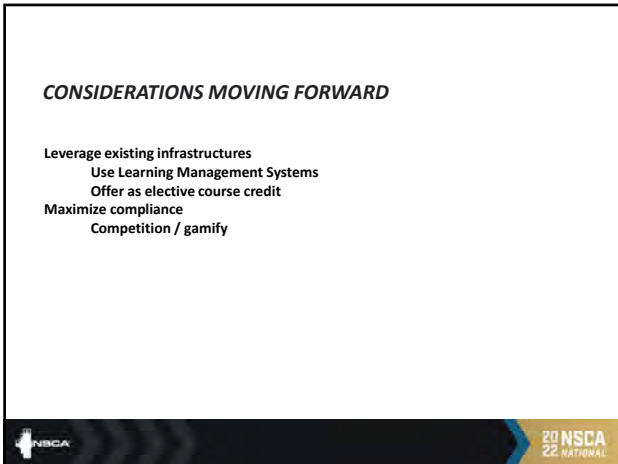
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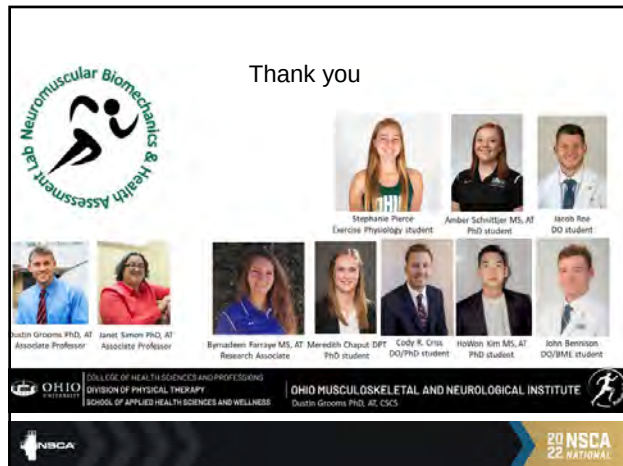
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Thank you!

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Can We Capitalize on Central Nervous System Plasticity in Young Athletes to Inoculate Against Injury?

Jed A. Diekfuss¹ · Jennifer A. Hogg² · Dustin R. Grooms^{3,4,5} · Alexis B. Slutsky-Ganesh⁶ · Harjiv Singh⁷ · Scott Bonnette¹ · Manish Anand¹ · Gary B. Wilkerson² · Gregory D. Myer^{1,8,9}

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Abstract

There are numerous physical, social, and psychological benefits of exercise, sport and play for youth athletes. However, dynamic activities come with a risk of injury that has yet to be abated, warranting novel therapeutics to promote injury-resistance and to keep an active lifestyle throughout the lifespan. The purpose of the present manuscript was to summarize the extant literature and potential connecting framework regarding youth brain development and neuroplasticity associated with musculoskeletal injury. This review provides the foundation for our proposed framework that utilizes the OPTIMAL (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) theory of motor learning to elicit desirable biomechanical adaptations to support injury prevention (injury risk reduction), rehabilitation strategies, and exercise performance for youth physical activity and play across all facets of sport (Prevention Rehabilitation Exercise Play; PREP). We conclude that both young male and females are ripe for OPTIMAL PREP strategies that promote desirable movement mechanics by leveraging a unique time window for which their heightened state of central nervous system plasticity is capable of enhanced adaptation through novel therapeutic interventions.

Keywords Musculoskeletal · Motor learning · Neuroplasticity · Development

The Problem: Anterior Cruciate Ligament Injuries in Youth

Sustaining an injury to the anterior cruciate ligament (ACL) can be physically, emotionally, and financially traumatic for a youth athlete, including potential premature closure to an athletic career [48] and greater long-term risk of osteoarthritis and reduced quality of life [126, 135]. Following the

initial injury (i.e., primary), reports of subsequent ACL re-rupture or contralateral ACL injury (i.e., secondary) within five years are as high as 23%, with youth athletes under the age of 25 being predominantly susceptible [3, 158]. Even when loss of function is restored and secondary injury is avoided, recent evidence indicates that successful return to pre-injury level of activity following ACL reconstruction (ACLR) is lower than formerly thought; approximately 35%

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⁹ The Micheli Center for Sports Injury Prevention, Waltham, MA, USA

of individuals suffering an ACL injury fail to return to previous activity levels [107, 143, 156]. The high re-injury rate and inability to restore functional capability indicates that current standards of care including ACLR and rehabilitation may not adequately address the deficits that may have preceded and/or propagated the initial injury [28, 56, 71, 129]. Novel therapeutic methods are therefore warranted to reduce re-injury rates, increase return-to-play rates, and improve post-injury quality of activity, particularly in youth athletes who are most susceptible to primary and secondary injury [118, 132, 158].

Current rehabilitation strategies for ACL injury focus primarily on restoration of neuromuscular function through muscle strengthening and neuromuscular control exercises [68, 146]. Though multiple factors can contribute to primary and secondary ACL injury, neuromuscular function is most readily modifiable, whereas other potential deficiencies, such as bony anatomy or circadian hormones, cannot be easily altered. Likewise, the goals of neuromuscular function focused rehabilitation have traditionally included restoring bilateral symmetrical motion, introducing safer movement patterns, and avoiding positions thought to excessively strain the ACL, such as dynamic knee valgus, knee hyperextension, tibial internal rotation, or stiff legged landings exhibited by minimal hip and knee flexion angles [14, 29, 71, 142, 152]. These aims are commonly accomplished by specific exercises addressing range of motion, muscle strength, proprioception, joint stability, endurance, and functional movement [40]. However, evidence indicates that youth athletes are often unsuccessful in their attempts to safely make the transition from the clinic to the playing field [55, 61]. Specifically, rehabilitation programs can improve lower extremity movement patterns associated with injury when assessed in the lab [11, 111–114, 116], but these improved movement patterns do not readily transfer to sport [32].

A number of factors may contribute to lack of motor skill transfer, including noncompliance with rehabilitation limiting skill acquisition altogether and/or the relative contextual simplicity of clinical rehabilitation in comparison to the intense demands of a competitive sport environment (i.e., the neurocognitive challenges associated with defenders, moving balls, targets, etc.) [65, 109]. Further, some commonly used metrics, such as bilateral symmetry, may not be as important as once thought, as hop testing symmetry does not mirror quad strength symmetry and restoring bilateral hop symmetry is not always effective for reducing ACL-reinjury [67, 75, 82, 100, 157]. Conversely, quadriceps strength deficits are well documented post ACLR and may provide a related indicator of residual deficits following surgery [120]. Compounding the injured limbs relative strength deficits, the uninjured limb typically also suffers decrements in strength and power post-surgery, potentially leading to altered biomechanics and masking of limb to limb deficits

[49, 117, 119]. Emerging neuromechanical evidence shows that post-injury altered biomechanics could, in part, result from unresolved alterations throughout the central nervous system (CNS) that affect both involved and uninvolved limbs following ACL injury and subsequent surgical reconstruction [81, 101, 145]. For instance, patients following ACLR exhibit differential knee-related brain activation in regions important for attention, vision, and sensorimotor integration compared to their non-injured peers [7, 8, 63], indicating aspects of normal CNS function may not be fully restored through rehabilitation. Thus, employing rehabilitation strategies that focus on addressing musculoskeletal system may restore symmetrical bilateral kinematics, but may overlook critical CNS impairments that allow for, and actually may underlie, subtle prolonged movement compensations.

The Solution: OPTIMAL PREP Strategies for Injury Resistant Movement

Recent evidence indicates that incorporating motor learning principles into rehabilitation protocols can improve landing mechanics for those recovering from ACL injury [53] and has been theorized to improve CNS function more broadly (non-specific to ACL injury) [160]. Considering that classic motor learning principles can be easily implemented through slight modifications in verbal instruction and feedback, such principles may be able to overcome the shortcomings of conventional ACL rehabilitation protocols by leveraging the brain's capabilities to positively adapt by targeting specific neural mechanisms via its potential for neuroplasticity [30]. While the concept of applying motor learning principles to ACL injury rehabilitation and prevention have been presented in the literature [12, 51, 52, 54, 55], clinicians, coaches, instructors, and athletes do not commonly implement motor learning theory principles within their clinic, on the practice field, or during athletic competition [39, 41, 64, 77, 134, 138, 154, 162]. A recent review provided the potential neural correlates and applications for various motor learning principles to ACL rehabilitation [54], and another clearly described related aspects of motor learning for clinicians aiming to enhance adaptive neuroplasticity post-ACLR [43], but neither report discussed recommendations within the context of the OPTIMAL (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) theory of motor learning [160]. Specifically, OPTIMAL theory identifies three distinct and partially independent motivational (enhanced expectancies, autonomy support) and attentional (external focus) motor learning factors/principles (i.e., “pillars”) theorized to leverage the capacity for CNS plasticity to achieve enhanced motor behavior through adaptive neuroplasticity [160]. Further, the pillars of OPTIMAL motor learning can be combined for more robust, additive effects [1, 23, 102, 103, 106, 128, 161],

but a conceptual framework for application of OPTIMAL theory in the context of ACL injury management strategies in youth—inclusive of prevention, rehabilitation, and exercise performance more generally—has yet to be proposed. A better mechanistic understanding regarding the role of motor learning on the CNS may help practitioners ‘buy-in’ and implement such methods in practice. For instance, applying more targeted and motivational approaches may lead to a more confident recovery, thereby increasing patient motivation and adherence allowing for the dosage needed to restore functional ability after injury [46, 151].

The purpose of this manuscript was to summarize the extant literature regarding youth brain development, as well as neuroplasticity associated with ACL injury. Specifically, we aimed to provide a conceptual framework for how the application of the OPTIMAL theory pillars could be applied to capitalize on youth neuroplasticity and elicit desirable biomechanical adaptations to support injury prevention (specifically reduction of injury risk), optimize rehabilitation strategies, and enhance exercise performance to support youth play across all facets of sport (Prevention Rehabilitation Exercise Play; PREP). “Youth” was defined herein as ~6 to 25 years of age and inclusive of pre-adolescence/pubertal, adolescence/post pubertal, and early adulthood. We selected a lower bound age range of ~6 years old indicative of the age period in which youth generally exhibit the requisite motor competence to benefit from training/resistance/agility programs, possess sufficient level of physical and emotional maturity, and/or is ready for structured sports participation [10, 91–96, 98, 99, 105, 115]. An older bound age range of ~25 years old was included to be cognizant of the college-aged participants that constitute the majority of studies providing empirical data for the neuroplasticity of ACL injury [122] and OPTIMAL motor learning [160], yet still within the age window that is burdened by such musculoskeletal trauma [76, 164]. However, we emphasize the described age window should not be considered fixed or restricted based on chronological number in light of various growth/maturational factors [9, 97, 104]. In fact, neurological, developmental-related factors could potentially amplify the relative effectiveness of OPTIMAL PREP strategies in the younger cohort of our age window (pre to early-adolescence vs. late adolescence/early adulthood), but will require implementation of these programs and further investigation to clarify with certainty.

ACL Injury and Neuroplasticity in Youth: An Overlapping Time Window

The inclusive youth age window of ~6 to 25 is intended to overlap between periods when ACL injury prevalence and incidence are high and when youth are undergoing a state of

heightened CNS plasticity. Data from the United Kingdom and Sweden show that ACL surgical repairs are most often performed in patients aged 20–29 [2, 3]. However, surgical rates in patients under 20 years old are rapidly increasing, with reports from 1997 to 2017 indicating more than a 20-fold increase [2]. The age window of surgical interventions for ACL injury is further modulated by sex. Prior to maturation, boys appear to be at greater risk of ACL injury; however, following puberty, ACL injury risk and incidence disproportionately increase in females [44, 73, 137]. Given these data, combined with secondary injury being most prevalent in youth under the age of 20 years old [158], youth may particularly stand to benefit from OPTIMAL PREP to enhance injury prevention programs for reduced risk for primary and secondary injury.

Throughout these time periods, and across the lifespan more generally, brain function and structure is malleable. However, during childhood and adolescence, many progressive and regressive functional and structural changes take place until more stable states are reached during young adulthood [148]. Specifically, longitudinal evidence from a large study of 387 subjects aged 3–27 years old, demonstrated that from early childhood to early adulthood white matter volume increases linearly (i.e., progressive change) and grey matter volume develops along a U-shaped curve (i.e., progressive and then regressive change) that peaks around age 8.5 years for females and 10.5 years for males [86]. These developmental changes result in the strengthening of connectivity between functionally-related, spatially distinct brain regions [155], as well as substantial reduction in synaptic density—otherwise known as synaptic pruning [130]—which accounts for grey matter loss during adolescence [74, 86]. Though males and females tend to follow similar trajectories of neurodevelopment, the age of peak regional grey matter when there is a switch from mostly growth to mostly synaptic pruning, is consistently 1–2 years earlier for females than males, but the rate of change is higher in males across childhood and adolescence [86]. Due to female neurodevelopmental trajectories peaking earlier than males, and physical maturational onsets earlier in females than males, researchers have tenuously suggested that the onset of puberty and sex hormones likely contribute to the earlier (younger age of onset) window for the onset of synaptic pruning [31, 45, 70].

At the individual level, the timeline for brain maturation varies; however, higher-order cognitive brain regions, such as the prefrontal cortex, generally mature after regions more important for sensorimotor control, such as the postcentral gyrus/primary somatosensory cortex [50]. Specifically, prospective longitudinal neuroimaging data (ranging from ~4 to ~21 years old) indicate that gray matter volume follows a “back-to-front” developmental trajectory as youth transition from childhood to early adulthood, such that occipital/

parietal lobes develop prior to the frontal lobe [50]. These findings can be attributed to functional, evolutionary milestones necessitating the need for basic sensorimotor control before higher level (i.e., top-down) cognitive functioning. However, in the context of sports, successful top-down processing in addition to fundamental sensorimotor functioning is vital to maintain injury-resistance during play [37, 38, 150]. Though the plastic nature of the brain is maintained across the lifespan, the robust changes in brain and behavior during the younger years [131] likely support an ideal time window to apply interventions that capitalize on the increased potential to influence injury-resistant neuroplastic adaptations.

The requisite for efficient top-down processing for youth injury resistance can be seen on an athletic field where athletes must execute appropriate motor responses while navigating a physically and cognitively demanding environment. Complex sporting scenarios exemplify the importance of successful communication throughout the nervous system, as errors in higher-level processing can instantiate a traumatic injury. For instance, ACL injury events occur more readily when an athlete is cognitively distracted (e.g., an incoming ball, surrounded by defenders) [72, 83], plausibly due to the CNS failing to anticipate, prepare, and/or correct a high-risk knee position. Thus, perception–action loops, or the higher-order ability to integrate sensory information with past experiences and prepare and execute the appropriate motor response, are vital for injury resistance, warranting approaches that can provide developmental synchrony between top-down processing and sensorimotor control. One means to accomplish this may be through physical activity due to its capability to improve both neurocognitive function [5, 24, 144, 149] and sensorimotor control in adolescents [35, 110, 115]. Further, youth physical fitness is associated with grey matter and white matter microstructure profiles more similar to young adults [69]. Thus, therapeutics for youth that include physical activity may foster enhanced injury resistance by supporting development of top-down processing at earlier ages, or at least shift the maturational timeline to occur more in tandem with sensorimotor cortical maturation.

Indeed, unique training frameworks have been developed and supported for implementation in youth athletes aimed to reduce the likelihood of such injury scenarios by leveraging the beneficial effects of physical activity on neurophysiologic development [42, 44, 45, 95, 96, 110, 115, 127]. While motor coordination does develop naturally, creating optimal learning environments for physical activity and individualized motor learning strategies can further enhance automaticity of motor control and retention of motor behavior [79]. To accomplish optimal learning environments, limitations with respect to motor learning literature should also be considered. Specifically, many classic studies use terms such as

“practice” or “acquisition” interchangeable with “training”, as they have relied on short-term interventions of one or two days and “retention/learning” assessments following rest periods as low as 20 min [139, 140] and typically not more than 24 h [78, 159, 160]. While still important contributions to the literature, the nuanced differences between motor performance and motor learning [79, 147] are not always clearly delineated, specifically as to whether a learned behavior may actually be retained for an extended time period. There is a critical need to create novel, individualized teaching and learning opportunities that promote long-term motor neurodevelopment and retention of training adaptations [6, 94, 127].

One example of such an environment is integrative neuromuscular training that incorporates general and specific strength and conditioning exercises, while also challenging neurocognitive and sensorimotor processes [110], that can reduce the risk of ACL injury [118]. Though the mechanistic influence of such programs on neurodevelopment has been primarily theoretical, the extant literature indicates that youth neuroplasticity is malleable and ripe for intervention-increased protective adaptations. The multimodal approaches combined in OPTIMAL theory may provide a pathway to enhance motor development in young athletes that increases injury-resistance across the lifespan. The recent proliferation of research into the neuroplasticity associated with ACL injury has revealed distinct alterations within the CNS (using methods including functional magnetic resonance imaging [fMRI], transcranial magnetic stimulation, etc.) (for a review see Neto et al. [122]), providing an opportunity to apply innovative techniques capable of treating both movement and CNS dysfunction simultaneously in youth, such as OPTIMAL PREP strategies. To support the subsequent neurophysiologic sections related to ACL injury, Fig. 1 is provided as general reference regarding the anatomy of the CNS related to neuromuscular control.

Neuroplasticity and ACL Injury

One factor driving the novel investigation of neuroplasticity and ACL injury stems from data indicates that these incidents typically occur in dynamic environments that simultaneously challenge multiple neural processing demands (e.g., integration of vision and proprioception inputs with cognitive decision-making when an athlete attempts to navigate through two defenders) [83, 84]. Indirect evidence of CNS dysfunction such as neurocognitive measures of reaction time and memory [150] indicates a potential predisposition for ACL injury that is unique from the classic neuromuscular [57] or biomechanical measures associated with ACL injury risk [71]. Further, emergent data of direct CNS dysfunction related to ACL injury (specifically within the brain and

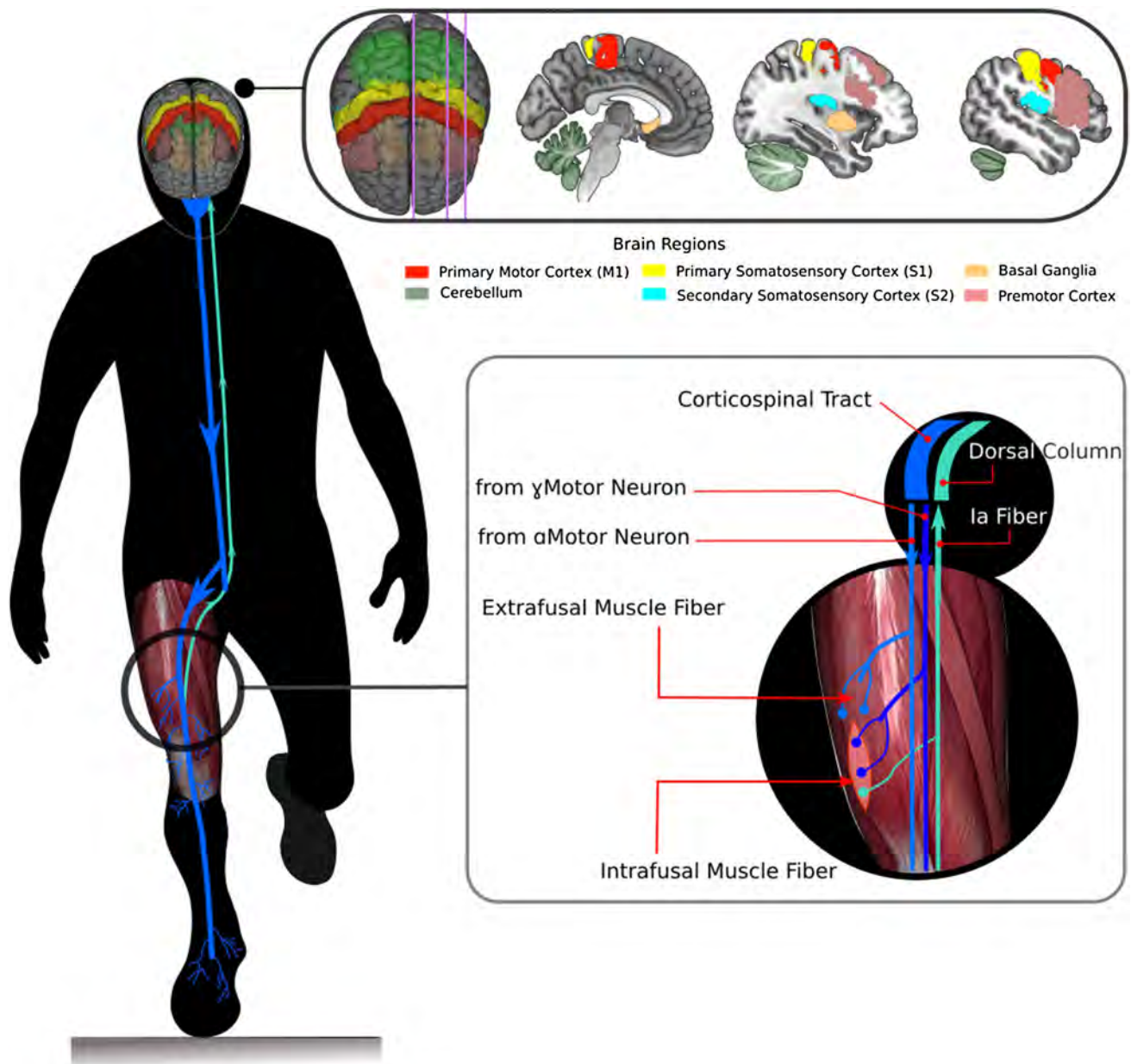


Fig. 1 General overview of key central nervous system components involved in neuromuscular/sensorimotor control. Though nearly all brain regions play some role in human movement depending on various constraints, we color-coded six brain regions particularly important for lower extremity, closed kinetic chain sensorimotor control (Grooms et al. [59]). In light of unique, individual anatomical struc-

ture, we determined the location of each brain region by using standard probabilistic atlases of the human brain with various thresholds to support presentation. The blue line represents the corticospinal tract and efferent information where it innervates with the musculature, whereas the teal line represents afferent information traveling from the musculature through the dorsal column and into the brain

spinal cord) has proliferated and generally fall into one of three categories in order of most empirical evidence: (1) CNS alterations following ACLR (2) CNS alterations that are associated with high ACL injury-risk biomechanics (e.g., aberrant frontal plane biomechanics) and (3) CNS dysfunction identified prior to future ACL injury. While a scoping review of these three topics are outside the aims of this report (see Neto et al. [122] for such a review), we briefly

describe each below to provide the foundation that supports the application of OPTIMAL PREP training strategies [34, 36].

Central Nervous System Alterations Following ACLR

Though a ligamentous injury such as an ACL rupture does not directly insult the CNS, disrupted afferent signaling from

the damaged/reconstructed ligament can propagate alterations in spinal and supraspinal function.[121]. One technique capable of quantifying supraspinal dysfunction is transcranial magnetic stimulation (TMS), which has been used in patients following ACLR [66, 87–89, 101, 123, 133, 163]. In brief, TMS applies magnetic fields to stimulate brain nerve cells (typically over the primary motor cortex to produce a musculature response at rest, i.e., resting motor threshold) or during an activity, i.e., active motor threshold) quantified with electromyography. In turn, these techniques can estimate the excitability of intracortical and corticospinal neurons that innervate specific musculature [141]. Regarding ACLR, the primary muscle group investigated is the quadriceps via numerous TMS techniques including single- and paired-pulse TMS and demonstrating altered intracortical and corticospinal excitability after injury compared to uninjured controls [87, 123, 163]. Further, elevated intracortical inhibition and depressed corticospinal excitability in patients following ACLR has been associated with reduced quadriceps voluntary activation [88, 101, 133], yet are limited by their failure to examine more widespread brain dysfunction beyond the primary motor cortex.

As cortical activity reflects a balance between inhibitory and excitatory circuits [22], electroencephalography (EEG) provides a means to supplement TMS-driven responses by measuring synaptic electrical activity throughout the cortex. Like TMS, there are numerous methods (e.g., at rest, during isometric muscular contractions, peripheral nerve stimulation) and techniques including somatosensory-evoked potentials and spectral analyses that have successfully demonstrated altered CNS function following ACL injury [7, 8, 25, 85, 108, 124, 125, 153]. For instance, by using EEG and asking patients following ACLR to complete joint position and force reproduction tasks, researchers have identified alterations in frontal theta and parietal alpha-2 frequency bands compared to the unaffected contralateral limb and/or controls [7, 8], potentially indicating a less efficient allocation of CNS resources towards somatosensory and attentional processing. Though these findings supplement those from TMS by showing CNS dysfunction that extends beyond the primary motor cortex, EEG is limited by recordings of superficial brain activity that precludes insight into potential subcortical functioning that is critical for motor control, such as the basal ganglia shown in Fig. 1.

fMRI and MRI allow for the measure of cortical and subcortical brain structure and function with higher spatial resolution relative to other described methods. Like the aforementioned instrumentation, numerous methods and techniques are possible by means of fMRI and MRI. These include and are not limited to studying brain function at rest and during movement via the blood oxygen level dependent signal, and brain structure at rest as determined by relative cortical thickness and white matter connectivity, all of

which can be analyzed over the whole brain or isolated to regions of interest. With respect to ACLR, task-based fMRI paradigms of unilateral knee flexion and extension movements have identified regional differences in blood oxygen level dependent signal activation/connectivity between those with ACLR and/or ACL deficient and controls [26, 62, 63, 80, 89]. Results from these studies have led researchers to hypothesize a framework whereby, following an ACL injury, patients switch from a sensory-motor to a visual-motor brain activation strategy for knee motor control [58, 63]. Supported by findings of increased activity in regions important for vision relative to sensorimotor control, these findings indicate that patients following ACLR rely more heavily on visual-proprioceptive processing following injury [21, 63], potentially due to internally-focused, visually guided and largely feedforward rehabilitation strategies with focus of attention on the joint or surrounding musculature. Recently, MRI-derived methods such as diffusion weighted imaging have even been combined with TMS to reveal neurostructural alterations for patients following ACLR, with less primary motor cortex excitability and alterations to the anisotropic/diffusion properties of the corticospinal tract observed [90].

CNS Alterations that are Associated with High ACL Injury-Risk Biomechanics

Emergent evidence has shown that athletes with poor neuromuscular control that have not experienced an injury or may have yet to experience an injury as signified by high external peak knee abduction moments during a drop vertical jump, eliciting resting-state electrocortical activity that may signify the CNS cannot effectively transition from rest to move states [19]. Technological improvements have advanced this line of research from resting to active states by developing MRI-compatible motion capture systems that can now be used to capture lower extremity biomechanics concurrent with CNS function derived from fMRI [4, 15]. Preliminary findings from our laboratory have revealed increased out-of-plane (frontal) knee angle associated with altered brain activity in regions important for attention, sensorimotor control, and sensorimotor integration while no similar in-plane (sagittal) neural correlates were identified [33]. Further confirming the CNS linkages to aberrant movement, preliminary findings demonstrated that overlapping, aberrant movement-associated increases in brain activity within the lingual gyrus were observed between two separate cohorts of youth soccer athletes completing a simulated bilateral leg press during fMRI [27]. Aberrant biomechanics were identified for one cohort by increased bilateral frontal plane knee loads during a drop vertical jump, and increased frontal plane motion during the actual fMRI task was identified using MRI-compatible motion analyses for the second

cohort [27, 60]. Cumulatively, the emergent literature with simultaneous measurement of CNS function with lower extremity biomechanics indicate distinct neural linkages associated with high ACL injury risk biomechanics.

Central Nervous System Dysfunction Prior to ACL Injury

Variations of the aforementioned methods and techniques have also emerged as relevant approaches to investigate CNS alterations prospective to the ACL injury event. To our knowledge, only two preliminary studies have prospectively used such direct measures—specifically resting-state fMRI—to evaluate CNS dysfunction prior to an ACL injury [37, 38]. Both studies, one with high school boys' football and one with high school girls' soccer, revealed reduced functional connectivity between regions important for sensorimotor control—some of which that are shown in Fig. 1—in athletes who went on to injury, compared to their uninjured peers. It was surmised that reduced functional connectivity, defined as the temporal correlation of the residual BOLD signal between spatially distinct brain regions [13], represented a potential predisposition for ACL injury, possibly reflecting poor sensorimotor CNS function that impeded neuromuscular control. The prospective findings relating CNS function with aberrant biomechanics indicate that CNS function should be considered along with biomechanical and muscular function for injury prevention strategies [35, 61, 136].

Collectively, data from TMS, EEG, and fMRI/MRI related to ACL injury have revealed distinct alterations within the CNS that could be targeted through neural mechanistic approaches, particularly in youth who are ripe for intervention-increased protective brain adaptations. Specifically, the robust behavioral literature supporting the OPTIMAL theory “pillars” of motor learning, as well as the theorized neural mechanisms of each principle, could potentially be used to uniquely target the neuroplasticity surrounding ACL injury [36]. Further literature provides more tangible examples of how OPTIMAL PREP strategies, such as “augmented” neuromuscular training [16–18] could be used to promote injury resistance [34].

Broad Application of OPTIMAL PREP Strategies in Youth

To enhance the clinical applicability, we have focused the current commentary on the neuroscience of ACL injury. Despite the noted sex- and age-related factors of neurodevelopment and ACL injury more broadly, OPTIMAL

PREP strategies are designed to be agnostic to sex. However, OPTIMAL PREP strategies may demonstrate amplified effectiveness if implemented at the earliest ages, but future research and supporting data is warranted to delineate and optimize the best timing to apply these interventional strategies. Further, we emphasize that the provided framework is also applicable for enhancing motor control for injury prevention, performance enhancement, and management of other youth musculoskeletal conditions such as patellofemoral pain or juvenile fibromyalgia. The opportunity to apply OPTIMAL PREP training strategies across the spectrum of youth populations is grounded in their heightened CNS plasticity more broadly [50, 131, 148, 155], making them uniquely suited for motor learning adaptations that can reduce injury risk and enhance injury recovery. For instance, children with developmental coordination disorder—a condition characterized by maladaptive motor development [47]—who completed a trail-tracing test elicited an altered brain activation profile [165] that shared similarities to patients following ACLR completing knee flexion and extension movements [63]. Specifically, both patient populations demonstrated increased activity in various occipital-parietal regions compared to controls when completing their respective sensorimotor-based tasks [63, 165]. OPTIMAL PREP strategies provide limitless potential for practitioners to apply techniques that target the aforementioned neural alterations [34]. For example, a clinician could aim to reweight their patients' brain activity in favor of sensorimotor activation using an external focus of attention [36].

Further, these strategies are relevant to motor control more generally and are designed to be agnostic to ACL injury. Specifically, the targeted population for OPTIMAL PREP strategies does not need to share an “overlapping” neural dysfunction to that reviewed for ACL injury, or even have measurable CNS dysfunction to begin with. For instance, a “visual-motor” brain activation strategy for knee motor control is present following ACLR [58, 63], but is not required for OPTIMAL PREP strategies to potentially be effective. Normal age-related structural development from childhood to adolescence of white matter fiber direction and gray matter volume important for sensorimotor control are intricately linked, potentially due to synergism between white matter expansion and gray matter contraction by means of myelination and synaptic/dendritic maturational processes [20]. The motivational pillars of OPTIMAL theory that include autonomy support and enhanced expectancies may be uniquely suited to exploit these neurodevelopmental processes as part of PREP strategies by releasing dopamine to modulate pre- to-post-synaptic transmission between neurons for enhanced sensorimotor control [36, 160]. Please see Fig. 2 that summarizes our theoretical framework to apply

OPTIMAL PREP strategies for injury resistance by capitalizing on their heightened CNS plasticity.

Summary and Future Directions

We have summarized the extant literature regarding brain development, neuroplasticity, and ACL injury within the context of a youth athlete. CNS linkages between aberrant movement and ACL injury, combined with youth neurodevelopment more broadly, indicate a unique window to apply OPTIMAL PREP strategies to achieve injury-resistance during play. Specifically, the positive brain

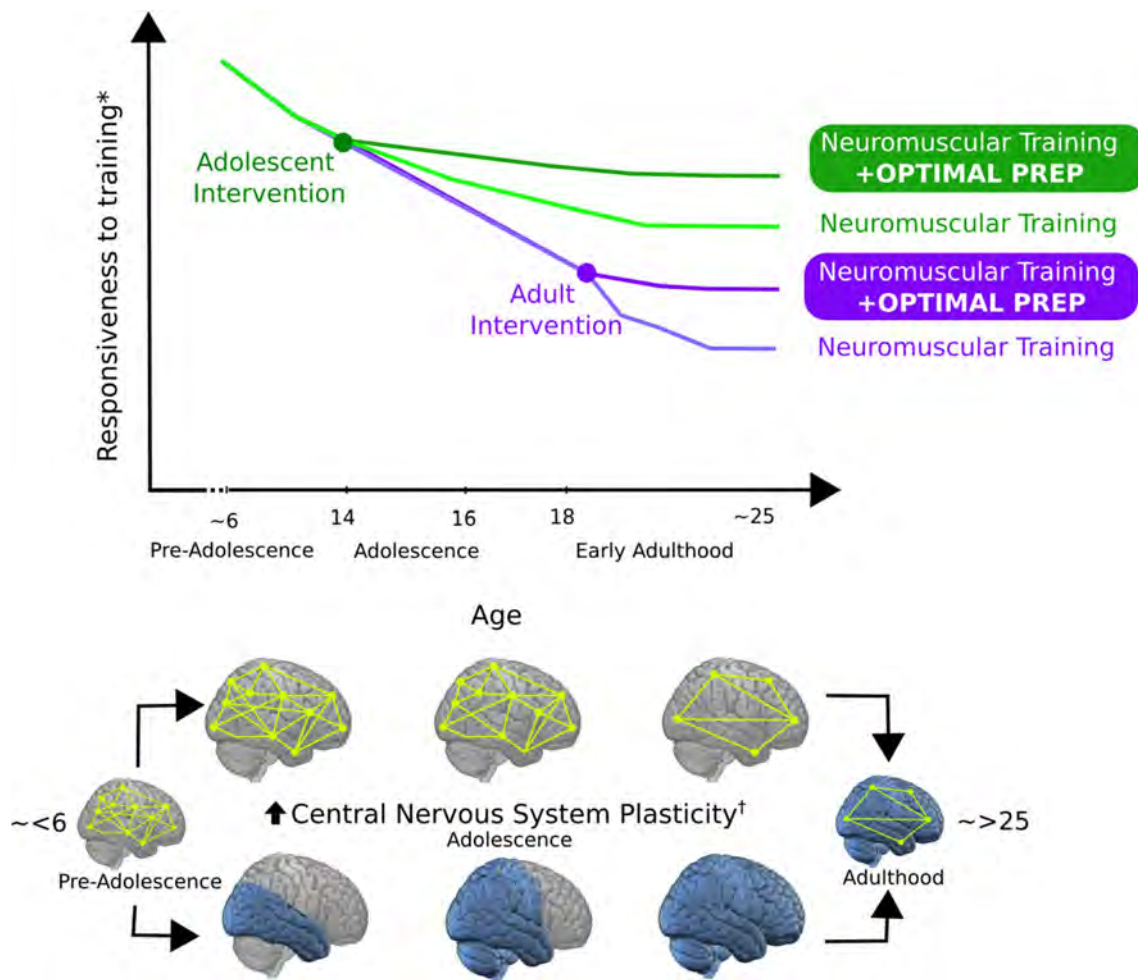


Fig. 2 Potential for OPTIMAL PREP strategies to accelerate injury resistance in youth: capitalizing on a unique time window of heightened central nervous system plasticity (~6 to 25 years of age). The line chart illustrates potential responsiveness to ACL injury risk reduction and neuromuscular training interventions across age/maturation status. *Responsiveness is operationally defined as subsequent risk for an ACL injury following completion of such a program; y-axis is approximate, but conceptually derived from relevant data in females that did not incorporate OPTIMAL PREP strategies [132]. Purple lines represent potential responsiveness if intervention is implemented in adulthood (light purple), and the potential for relatively enhanced responsiveness if OPTIMAL PREP strategies are additively incorporated (dark purple). Green lines represent respon-

siveness if intervention is implemented in adolescence (light green), and the potential for amplified responsiveness if OPTIMAL PREP strategies are additively incorporated (dark green). Brain images with yellow lines depict heightened synaptic pruning [130], and progressively increased blue brain shading represents the trajectory of gray matter maturation from parietal-occipital to frontal lobes [50]. †Central nervous system plasticity is generally considered most robust and responsive during “youth” versus middle and late adulthood. However, the immense variability of neuroplastic changes (e.g., cellular, structural, functional; often context- or individual-specific) require future investigation within the context of OPTIMAL PREP application before more defined age windows can be clarified

adaptations we anticipate in response to OPTIMAL PREP strategies are designed to be applicable to a variety of populations throughout the formative developmental years for those with and without movement disorders.

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Targeted Application of Motor Learning Theory to Leverage Youth Neuroplasticity for Enhanced Injury-Resistance and Exercise Performance: OPTIMAL PREP

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Abstract

Youth athletes are ideal candidates for novel therapeutic motor learning interventions that leverage the plasticity of the central nervous system to promote desirable biomechanical adaptations. We summarize the empirical data supporting the three pillars of the Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) theory of motor learning and expand on potential neurophysiologic mechanisms that will support enhanced movement mechanics in youth to optimize prevention programs for reduced injury risk, injury rehabilitation, exercise performance, and play (Prevention Rehabilitation Exercise Play; PREP). Specifically, we highlight the role of motivational factors to promote the release of dopamine that could accelerate motor performance and learning adaptations. Further, we detail the potential for an external focus of attention to shift attentional allocation and increase brain activity in regions important for sensorimotor integration to facilitate primary motor cortex efficiency. This manuscript serves to provide the most current data in support of the application of OPTIMAL PREP training strategies of the future.

Keywords Dopamine · Musculoskeletal · Exercise performance · Motor behavior

Introduction

Youth sports participation promotes long-term psychosocial and athletic/physical development [66, 71, 133, 135, 136, 170], assuming they exhibit satisfactory motor competence, physical maturity, and general emotional/psychological readiness [20, 131–134, 137–139, 149, 156]. However, youth

sports participation comes with a risk of experiencing a sports-related injury. One injury of particular concern is the anterior cruciate ligament (ACL), as it commonly requires surgical reconstruction (ACLR), extensive rehabilitation of upwards of one year before returning to play [206], and can drastically increase an athlete's long-term risk of disabling knee osteoarthritis [93, 178]. Considering the increase in

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ACL injury incidence among youth [223], combined with a significantly higher risk of subsequent (secondary) re-rupture or contralateral ACL injury [226], supplemental methods to enhance current rehabilitative standards of care are warranted. Specifically, observations of lingering deficits to motor function/control, including limb asymmetry, aberrant movements in both the injured and uninjured limbs during landing and jumping, and reduction in quadriceps strength, [78, 130, 167] all highlight potential shortcomings with current strategies following ACLR and rehabilitation [205]. Emergent evidence further implicates alterations to the brain and spinal cord post ACLR [i.e., central nervous system (CNS); neuroplasticity] that persist years after completion of formal therapy and return to play [15, 16, 43, 85, 124, 127, 159, 250].

CNS changes associated with ACL injury and motor development, make the implementation of strategies that promote injury-resistant adaptive neuroplasticity potentially even more impactful in pediatrics [56]. Neuroscientific data indicate that youth may be of an ideal age to intervene and promote positive neuroplastic adaptations by capitalizing on the malleability of the human brain throughout the lifespan [96, 120, 168, 207, 218]. Notably, various components of motor learning have gained considerable attention as a means to induce neuroplasticity [45, 79], with a recent framework (Optimizing Performance Through Intrinsic Motivation and Attention for Learning; OPTIMAL) proposing three specific motor learning factors/principles (i.e., "pillars") theorized to enhance motor performance and learning by leveraging individuals' capacity for CNS plasticity through adaptive neuroplasticity [240]. The pillars of OPTIMAL theory—enhanced expectancies, autonomy support, and an external focus of attention—could potentially elicit desirable biomechanical adaptations in youth to optimize injury prevention strategies (specifically the reduction of injury risk), injury rehabilitation, exercise performance, and play across all facets of sport (Prevention Rehabilitation Exercise Play; PREP) [56].

The purpose of the present manuscript was to review the three pillars of OPTIMAL theory for heightened motor learning, the potential neural mechanisms, and specifically the CNS plasticity to support the widespread application of OPTIMAL PREP. We frame our neurophysiologic mechanisms and examples of OPTIMAL PREP strategies in the context of ACL injury, but emphasize their potential utility across a range of youth musculoskeletal disorders and for exercise performance, injury risk reduction, injury rehabilitation, and play more generally. To note, "youth" is discussed as encompassing both males and females between the approximate ages of 6 and 25 years, congruent with previous OPTIMAL PREP literature [56]. However, we emphasize that this age range is intended to be largely inclusive of pre-adolescence, adolescence, and early adulthood, and not

restricted to any chronological age or sex despite growth/maturation factors [17, 137, 148]. Though we do support the notion that OPTIMAL PREP effects could be amplified if implemented during pre- to early-adolescence to capitalize on neurologic, developmental-related factors (e.g., synaptic pruning) [56], longitudinal data is needed to confirm a more refined age window. We also premise this review by operationally defining motor performance as temporary, transient changes in a motor skill; whereas motor learning is defined as the relatively permanent changes in a motor skill as a direct result of practice or experience [200, 244].

Pillar 1: Enhanced Expectancies

Confidence has been recognized as a predictor of motor performance in adolescents [214]. As levels of confidence rise, one's subsequent performance is also enhanced, and learning is reinforced. Within our OPTIMAL PREP framework, we operationally define "enhanced expectancies" as purposeful manipulations within training environments that safely enhance a learner's confidence for achieving success in a prescribed task. This is contrasted to standard training that focused on task performance alone without considering methods to amplify task-related confidence of the learner. Conditions that enhance patient expectancies for success can provoke greater feelings of accomplishment while improving performance and learning that detracts focus on the self, such as worrying about how someone else may view his or her own performance [153, 189, 239]. An example of such an undesirable response from expectancies could be an athlete recovering from an ACL injury having just completed a muscle-strengthening rehabilitative exercise with neutral feedback (i.e., "please complete these exercises again"). The failure to provide positive, reassuring feedback could "trigger" a detrimental, self-fulfilling prophecy to cyclically worry about the self, promoting inward focus of attention. Thus, practice conditions that promote success (i.e., a physical therapist suggests that his or her patient will reach a new goal load or weight if they can complete the set again) could reduce the likelihood for internally-focused/self-regulatory thought processes that disrupt movement automatization and thus have more direct motivational influences.

According to the OPTIMAL theory of motor learning, strategies to enhance expectancies include positive feedback, social-comparative feedback, conceptions of ability, self-modeling, and perceived task difficulty [240]. For example, feedback after good trials or the most effective trials, as compared to feedback after poor trials or least effective trials, enhances learning [37, 192], competence [192], and self-efficacy [191]. When providing positive social-comparative feedback, operationally defined as instructing a performer he/she behaving better than his/her peers even if that

feedback is inaccurate, demonstrates improved participant performance, learning, and physiological efficiency [9, 95, 128, 209]. Such positive feedback can promote higher self-perceived competence [236] and likely plays a significant role in the observed improvements in motor performance and learning. However, when specifically applying social-comparative feedback, practitioners should be aware of unintended consequences that arise from comparing one learner to another, or telling a child that he/she is performing better than their peers. This form of feedback could foster an ego-oriented mindset, broadly defined as success or failure based on personal performance that is relative to peers/extrinsically validated, whereas a task-oriented mindset places higher value on task mastery/intrinsically-related personal improvement [141, 142, 158]. An ego-oriented mindset may be of particular concern in youth, as some evidence indicates that those under the age of 12 have trouble differentiating whether concepts of luck, task difficulty, and effort are the contributors or determinants of athletic success [158]. Despite some general controversy and reasonable concern about ego-oriented mindsets in sport, a meta-analysis did not fully confirm such a claim as numerous exceptions and limitations to prior research exist [142]. Nevertheless, we still recommend employing social-comparative feedback with consideration, at least until clarified with future research. For instance, minimizing an ego-oriented mindset could potentially be accomplished by purposefully comparing a learner's progress to historical normative performance of a generic population, or perhaps a former teammate in seasons past, to reduce the potential for immediate and easy comparison to a friend or teammate.

Enhanced expectancies can also be achieved by manipulating an individual's perception of task difficulty such that it is perceived easier [11, 12, 32, 34, 163, 231] and/or altering the criterion for success by providing easier objectives earlier in practice [213]. For instance, youth and adult target-aiming performance and learning is improved when participants aim towards a target that appears larger by surrounding it with smaller targets to manipulate the perception of its size [11, 12, 34, 163]. However, similar to the caution required if implementing social-comparative feedback, the potentially beneficial motor performance/learning effects when providing false positive feedback and/or manipulating perceptions of task difficulty requires consideration. In a rehabilitation scenario, deceiving patients (i.e., providing false positive feedback or manipulating their perceptions of task difficulty) could actually amplify their risk of primary or secondary injury if their psychological readiness/confidence/fear of re-injury supersedes their physical capability. For instance, patients following ACLR who possess high fear of re-injury concomitant with deficits in function (e.g., quadriceps strength) should not necessarily employ enhanced expectancies to increase confidence as a patient's

confidence level is matched to their physical status [121]. To artificially increase confidence in such a patient may be counterproductive as they may believe they can return to play, but are physically not ready. Specifically, manipulating confidence should generally reflect patients' physical capability, however, these variables are not always related, indicating distinct constructs [160, 186]. Evidence in this area is evolving with some studies indicating that higher psychological readiness is associated with better function and may reduce the risk of secondary injury upon return to sport [21, 154, 166, 222]. However, no study has yet intervened on psychological readiness to determine if doing so would reduce second injury risk or encourage over-confidence and potential premature sport activity and elevated injury risk. In light of the strong behavioral data derived from classic motor learning/sports performance studies [240], we still encourage this pillar, but emphasize that when deception is involved to manipulate confidence for patients (particularly in medical contexts) or when social-comparative feedback is employed, tasks and feedback must be purposefully designed with patient safety and the patients' feelings of oneself or others as utmost priorities.

Furthermore, responses to such performance feedback depend on whether one possesses an appropriate perspective regarding the malleability of their psychological attributes [173]. Self-modeling, operationally defined as when learners' are shown edited videos of their best performances and/or peers they relate to and are told to repeat it, is one method helpful for accurately developing an individual's conceptions of actual versus perceived performance [227]. For instance, participants who were shown models of peers performing appropriate time-matched rehabilitation exercises decreased their perceptions of expected pain and increased rehabilitation self-efficacy [145]. Self-modeling should also be purposefully implemented as it not only increases motor skill learning, but also results in greater intrinsic motivation and satisfaction with performance in motor coordination tasks including balance, swimming, and trampoline skills [40, 208]. Simply put, enhancing expectancies during practice can elicit higher levels of confidence, higher performance competence, and motivation which in turn may allow youth more movement automaticity.

Pillar 2: Autonomy Support

Autonomy support is another pillar of the OPTIMAL theory of motor learning that leverages motivation to achieve success [240]. Autonomy refers to an individual's need to actively participate in one's own behavior and is considered both a fundamental psychological need [48, 49] and a biological necessity [123]. Converging evidence indicates that providing individuals with a degree of self-control enhances

motivation/self-efficacy, quality of life, motor performance, and motor learning [38, 105, 197]. The OPTIMAL theory describes several ways to incorporate autonomy support, including providing an individual with control over their practice conditions, supportive instructional feedback, and numerous opportunities for task relevant and/or incidental choices. Self-control over practice conditions, such as allowing the individual to choose the order in which tasks are completed [235] or the number of practice trials to be completed [177], has repeatedly shown to improve motor performance and/or learning [35, 100, 210, 233, 243].

Permitting individuals to have control over at least one aspect of their practice environment allows them to individually tailor practice to their own capabilities [210, 233]. Similarly, giving individuals the opportunity to choose when to receive verbal feedback [35, 36, 100], when to observe model demonstrations [36, 119, 243], or when to utilize an assistive device [90, 247] have all resulted in improved motor performance and learning compared to controls given no choice. Interestingly, incidental choice, operationally defined as trivial and outcome-irrelevant choices, can also improve the primary task. For instance, providing individuals the option to choose the color of a golf ball improved golf putting performance, and even more incidental and trivial, letting individuals choose the artwork to be hung on a laboratory wall improved balance performance [90]. Because control participants are typically "yoked" such that they receive an identical practice environment by matching the time of delivery to those in the autonomy conditions, improvements are considered a reflection of one's perception of control and not simply a product of differential practice conditions.

Allowing autonomy over aspects relative to the task goal as opposed to irrelevant aspects also leads to differing results in highly motivated versus unmotivated learners [97]. If the learner is intrinsically motivated and naturally competitive, giving task-irrelevant autonomy may be less beneficial, and may be slightly harmful to learning. Task-relevant autonomy, however, is effective for both the motivated and unmotivated learner [97], thus providing task-relevant autonomy supportive (i.e., "asking" someone what to do) rather than "controlling" language (i.e., "telling" someone what to do) can promote positive affect and indirectly boost motivation for enhanced learning [94]. Specifically, providing clear explanation and supporting rationale for why a behavior should be changed, carefully considering the athlete's perspective with empathy, providing various selectable solutions to overcome an obstacle, and avoiding language perceived as shameful or punishing can maximize the relationship between the instructor and learner and enhance performance [33, 88, 152, 210]. However, similar to enhanced expectancies, autonomy support also requires careful consideration before it is employed in youth populations. For instance,

compared to a psychologically mature 18-year old athlete, a six-year-old is likely more accustomed to, and relies more heavily, on others for decision making regarding their health and well-being. Providing numerous choices to a psychologically immature 6-year-old may elicit undesirable feelings of anxiety, worry, etc., particularly if the athlete is concerned about making what he or she perceives as the "correct" or more favorable decision. Similarly, experience and expertise in numerous tasks may be more limited in the six- versus 18-year-old. For example, choosing when to receive kinematic feedback during a golf putting task may not be effective to the inexperienced six-year-old, but incidental choice, such as letting him or her select the color of the golf ball may still be beneficial to enhance motor learning. We thus emphasize that autonomy-supportive environments be created in a purposeful manner that reflects the psychological maturity, experience, and expertise, of a given athlete.

Pillar 3: An External Focus of Attention

Instruction and feedback serve as important components for motor performance, learning, and exercise performance more broadly [200, 228, 229]. A critical observation over the past two and a half decades has been that motor outcomes can be manipulated via subtle, often single-word changes to instructions or feedback [234] and recommendations have recently been made. Classically, the direction of attentional focus has been dichotomized as being either internal or external [238], though it is increasingly noted that attentional focus can be neutral (e.g., "jump as high as you can") or even "holistic" in that emphasis is placed on the general feeling of a movement, often with the use of adjectives and adverbs (e.g., "concentrate on feeling smooth") [19, 161]. Typically, coaches and clinicians tend to utilize what is deemed an "internal focus" whereby attention is directed towards the coordination of body segments [238], such as the position of knee when landing, movement form, etc. [58, 64, 88, 217]. Despite athletes' attention being dynamic and adaptable during practice and competition [10, 25, 59], athletes mostly report concentrating on body movements [58, 176], even without explicit internally-focused instruction [86]. However, empirical data has repeatedly shown that adopting an external focus of attention, defined as concentrating on the intended movement effect (e.g. the flight of a ball) [238] significantly enhances motor performance and learning relative to an internal focus (i.e., focusing on body movements) [234].

An external focus has robustly demonstrated enhanced performance and/or learning in numerous motor tasks including balance control [57, 60, 118, 164, 187, 246], basketball free throw shooting [6], discus throwing [249], reaction and movement preparation time [113], sprint

speed [98], and jump/hop distance [174, 175, 182, 232]. More specifically, an external focus has resulted in more effective (e.g. increased movement accuracy) [180, 185, 245], efficient (e.g. reduced muscular activity) [219, 237, 248], and automatic movements (measured using dual-task costs) [102]. Accumulated evidence in support of an external focus has also demonstrated its role in optimizing movement form [3] and promoting enhanced physiologic functioning as defined by reduced oxygen consumption during endurance running [201]. According to the constrained action hypothesis [242], an internal focus of attention constrains the system by freezing/constraining biomechanical degrees of freedom through the conscious control of movement processes. In contrast, an external focus promotes the utilization of more automatic, reflexive, and fluid movement [102, 219, 242]. Despite external focus being robustly effective to those of various ages, such cueing and feedback may be particularly efficacious for younger youth age groups during training by uniquely capitalizing on developing neurophysiology [14]. In fact, emergent data has further revealed that, during a drop jump, delivery of different external cues associated with sound, height, or ground contact time elicited biomechanical responses that were uniquely cue-specific in youth soccer players [161]. Importantly, these data demonstrated that the external cues enhancing performance did not always improve biomechanics associated with ACL injury risk [161]. We support their general conclusions within our OPTIMAL PREP framework; coaches and clinicians should pursue and prioritize external cues that promote desirable, injury-resistant movement mechanics over performance outcomes when training youth.

Indeed, relative to enhanced expectancies and autonomy support, the potential benefits of an external focus have received considerably more discussion with respect to ACL injury prevention programs and injury rehabilitation [22, 75, 76, 79, 80], yet still have limited support from empirical data, particularly for patients following ACLR. Though a few additional studies have examined the effects of an external focus for improving biomechanics associated with ACL injury risk [23, 24, 69, 184, 224, 225], to our knowledge only a handful of studies have investigated the effects of an instruction-based external focus for patients rehabilitating from ACLR [5, 77]. Notably, other studies have successfully used augmented feedback techniques to improve ACL injury risk biomechanics via visual stimuli presentation of video feedback compared to or in place of verbal, externally-focused feedback [28, 29, 67, 68, 157]. However, from a mechanistic perspective, providing feedback via visual stimuli relative to verbal instruction elicits considerably different neurophysiologic responses, evidenced by greater visual-related brain activity when additional visual stimuli are added to externally-based instruction [181].

Due to the aforementioned methodological differences, the "how" underlying the beneficial effects of an external focus have recently become even more muddled. For instance, in a recent systematic review [8] the authors incorrectly categorized such augmented feedback studies—studies using complex, technology-based presentation of visual feedback—into the direction of attentional focus by defining an external focus as “attention paid to the outside of the body”, which is notably different from the literature-established definition of “attention directed towards the intended movement effect” [238]. Further, a driving principle underlying OPTIMAL theory’s definition of an external focus is that performance effects are independent [1] and not mediated by visual information [117]. In other words, an external focus requires “concentrating on a movement effect”, not necessarily “looking” at a stimulus. Nevertheless, both approaches have had clinical success for ACL injury rehabilitation, thus we discuss external focus by being inclusive of both feedback delivery methods and clarify the differences by “instruction-based” external focus vs. “technology-based” external focus as appropriate.

As many instruction-based external focus studies do include added visual stimuli [174, 182], we operationally differentiate these methods from technology-based approaches based on the relative differential complexity of the visual stimuli. Specifically, when instruction-based studies have used a visual stimuli to induce an external focus, it is typically by directing attention towards a simple, stationary object that does not adapt in real-time, such as a cone to jump to, a dart board to throw too (low complexity). Indeed, one of the most extensive training studies of attentional focus in terms of practice—8 weeks of neuromuscular training—found potentially beneficial effects of external focus with simple visual stimuli of low complexity [73]. Despite the considerable contribution of this study from a clinical perspective, we still consider it limited from a theoretical perspective. Specifically, there was no instruction-only external focus group or an internal focus group with matching visual stimuli to differentiate whether instruction or visual-associated CNS processing was driving the observed changes in motor performance/learning. In contrast, many technology-based approaches utilize nonstationary visual stimuli that are driven from real-time biomechanical data to induce an external focus, such as an interactive geometric shape that is constantly moving and displayed in virtual/augmented realities (high complexity) [27, 29, 53, 84]. Easily implemented, OPTIMAL PREP clinical examples for how instruction-based external focus with and without added simple visual stimuli, as well as advanced technology-based approaches capable of administering both simple and complex feedback and instruction, are described in detail elsewhere [52].

Interaction of Pillars: Synergistic and Additive Effects

Though the OPTIMAL theory is still relatively new, emerging evidence is confirming the benefits of additive effects for each partially independent factor [2, 39, 146, 147, 150, 165, 241]. Specifically, compared to one factor, the combination of two factors has been shown to result in greater performance and learning [146, 150, 165], with the combination of all three factors shown to additively improve motor performance [2, 39]. For instance, asking athletes to focus externally and providing them with autonomy support while performing soccer penalty kicks improved performance relative to a control or isolated autonomy support conditions (i.e., with no additive external focus) [146]. Likewise, performance was enhanced during a nine-pin bowling task when participants were provided autonomy support, enhanced expectancies, and asked to focus externally (relative to "neutral"/isolated conditions) [2]. However, to our knowledge no studies have systematically examined the additive effects of combining OPTIMAL motor learning pillars within the context of PREP strategies for youth. Further, the potential manner in which these factors interact across the youth age spectrum has not been established. There is likely a combination of pillar (s) that promotes superior movement outcomes given the individual, task, and environmental constraints in which they are applied. Despite the need for future research, motor performance and learning literature indicates that all youth—regardless of the type or even presence of musculoskeletal conditions—could potentially amplify their trajectory for injury resistance when the pillars are used purposefully, safely, and potentially additively. For instance, cognitive behavioral therapy (CBT) has recently shown promise for enhancing psychological factors (e.g., fear avoidance, self-efficacy) for patients recovering from ACLR [42], thus could potentially be further enhanced through the systematic inclusion of enhanced expectancy methods, particularly if combined with motor-based rehabilitative methods. Illustrative examples with respect to youth are evidenced by the combination of CBT with integrative neuromuscular training to reduce pain, increase self-efficacy, and enhance movement mechanics in patients with juvenile fibromyalgia [106–108, 211, 212].

Potential Neuroplastic Mechanisms for Enhanced Expectancies and Autonomy Support

Enhanced expectancies and autonomy support are theorized to increase motivation, promote dopaminergic transmission, and strengthen brain functional connectivity (both within and between various brain networks) [240]. Musculoskeletal injuries, specifically an ACL injury, is not only a structural disruption [4, 99], but also a concomitant deafferentation injury [216] whereby lost mechanoreceptors and disrupted afferent pathways contribute to maladaptive CNS plasticity [104]. Patients following ACLR show reduced spinal reflex excitability [92, 124, 126, 172], and altered corticomotor excitability [91, 124–126, 172] that may make them uniquely responsive to the neurological implications of enhanced expectancies and autonomy support.

Motor performance and particularly movement speed and reaction time—termed ‘vigor’—are highly influenced by relative neurological effort-reward calculations occurring within the basal ganglia and associated dopaminergic system [62, 203]. Dopamine—a neurotransmitter—is produced in midbrain neurons that send their axons throughout the brain [26]. Specifically, the firing of these neurons broadly releases dopamine into neural tissue that indirectly modulates pre- to post-synaptic transmission [162]. Dopamine influences motor control through corticostriatal circuits and the basal ganglia [13, 87]. More specifically, the ventral and dorsal striatum, nucleus accumbens, globus pallidus, substantia nigra, and subthalamic nucleus are all involved in effort-reward pathways, movement initiation, and motor planning [46, 51, 72, 204]. As the evaluation or perception of effort decreases or reward increases, movement speed tends to increase secondary to dopamine release within the striatum of the basal ganglia [13, 87]. While no evidence has directly connected ACL injury to impairments in the dopaminergic system, ACL deficient patients do, in fact, have altered basal ganglia activity [104]. Further, reduced rate of muscle force development and slower gait speed after injury is associated with worse patient outcomes, reduced corticospinal excitability, altered joint loading and greater cartilage degrade [44, 111, 169, 171, 199], providing opportunities for interventions that enhance movement vigor to potentially uniquely benefit the neural mechanisms of post-injury motor system impairments.

Fundamentally, both enhanced expectancies and autonomy support influence relative effort-reward behavior to evoke a positive response from the dopaminergic system [112, 202, 240]. While both enhanced expectancies and autonomy support can increase relative perception

of movement-based reward, enhanced expectancies can also modulate perception of effort. For instance, when told their running style was particularly efficient, runners subsequently decreased oxygen consumption and reported greater ease and less fatigue with running [209]. Movement initiation is particularly dependent on effort perception and basal ganglia activity [83] via dopaminergic neurons that further mediate movement initiation by exciting the striatum [50]. A prominent feature of many ACL injury prevention programs and/or injury rehabilitation programs are exercises that require movement initiation, such as squatting and jumping [31, 155], providing exercises that are easily modified with enhanced expectancies to reduce perceived effort, increase dopaminergic-related activity, and untimely enhance motor performance/learning.

The altered functional connectivity throughout regions important for sensorimotor control observed for patients prospective to ACL injury [54, 55] may support enhanced expectancies and autonomy support to increase movement-associated reward. A form of autonomy support in which individuals provided a 'goal choice' not only involves regions important for sensorimotor control such as the primary somatosensory cortex [65], but also engages the ventrolimbic system including the ventromedial prefrontal regions and ventral striatum [198, 215]. The striatum is further associated with the provision of personal choice [122] and converging neuroscience evidence robustly indicates this region as distinctly important for motor learning [116].

As the expectation of reward derived from an individual's goal choice can trigger a dopamine response throughout fronto-striatal circuitry for enhanced motor function [202], adding choice may enhance connectivity between limbic and sensorimotor brain regions. Specifically, re-triggering stimulus-reward scenarios may not only boost transitory motivation, but promote long-term memory consolidation for enhanced learning [230]. Specifically, the mesocortical pathway—one of the various dopaminergic pathways which connects the ventral tegmentum within the midbrain to the prefrontal cortex—could be triggered during repeated, choice-reward scenarios. For instance, this could be accomplished by providing choice of rehabilitation exercises at the start of every session [52]. The positive affect associated with such rewards may trigger dopamine to be released throughout the mesocortical pathway, thereby priming the prefrontal cortex for enhanced learning [190]. Notably, this is just one example as dopamine is also transmitted through other distinct pathways (e.g., nigrostriatal, mesolimbic), plausibly promoting adaptive neuroplasticity in other brain regions.

The use of enhanced expectancies and autonomy support to increase the perceived reward of movement also has ready potential to enhance ACL injury rehabilitation via cortical excitability modulation. The pathways of the basal ganglia

serve a prominent role to inhibit cortical drive to the spinal motor neurons, inhibit thalamic drive, and ultimately raise the excitability of the motor cortex to initiate movement. As ACL injury is associated with reduced corticospinal tract excitability and potential atrophy [124–127, 144, 172, 188], targeting of corticostriatal circuitry using effort-reward modification may positively influence desired behavioral adaptations. In fact, evidence indicates that patients who have strong expectations for receiving the best treatment relative to a placebo have demonstrated increased dopamine release in the ventral striatum [129, 221], plausibly capable of increasing synaptic transmission between and within key sensorimotor regions and elevating cortical excitability via dopaminergic pathways. The dopaminergic response for such effort-reward manipulations likely modulate numerous cortical and sub-cortical networks important for motor learning including, but not limited to, the salience, sensorimotor, frontoparietal, dorsal-attention, and default mode networks, though further study is needed [89, 143]. In Fig. 1, we provide an example of the theorized dopamine response from enhanced expectancies during a single leg landing task. In Fig. 2 we provide an example for autonomy support for ACL injury rehabilitation and the theorized neural mechanisms. Further clinical examples for both motivational pillars are provided elsewhere [52].

Dopamine and the Youth Athlete: Clarification Before Implementation

As described, autonomy support and enhanced expectancies are theorized to elicit enhanced injury resistance in youth by an adaptive dopamine response. Though the seminal paper proposing OPTIMAL theory elegantly described a few scenarios and conditions that may trigger dopamine during motor performance/learning interventions [240], critical factors for translating findings from the lab to a sport or clinical setting require further exploration. For instance, OPTIMAL theory predictions (Table 1: Wulf and Lewthwaite [240]) include brief summaries of how a dopaminergic response could be achieved, including (a) temporally associating enhanced expectancies during "skill practice", (b) generic use of "enhanced expectancies and autonomy support to facilitate motor learning", and (c) providing "challenge" in the context of prevailing success. A key aspect of these suggestions is that they have some temporal or context relation to the motor skill and not to be misconstrued and achieved by completely irrelevant factors, including nutrition, sleep, supplementation, meditation, or simply listening to music, that are all known to regulate dopamine response [30, 70, 81, 109, 110, 151, 220], but do not directly influence motor skill learning.



Fig. 1 Left image (green border) demonstrates a patient performing a single leg drop landing after receiving positive feedback to enhance their expectancies. In addition to better neuromuscular control (demonstrated by them ‘sticking’ the landing), and shown by the blue dots, dopamine is theorized to be released from the substantia nigra* (medial inferior red cluster) into the ventromedial prefrontal cortex^ (anterior red cluster). The corticostriatal circuit (green arrows) may also facilitate dopamine transmission into regions important for sensorimotor control including but not limited to the primary somatosensory cortex (superior red cluster). Right image (red border) demon-

strates the participant completing the same task but with feedback that fails to promote enhanced expectancies. As such, their neuromuscular control is poorer shown by their inability to stick the landing and their dopamine transmission is limited shown by no dopamine release/blue dots. *We emphasize that dopamine can also be released from other regions including, but not limited to, the ventral tegmental area. ^Dopamine is also released into other regions including, but not limited to, the ventromedial striatum, which may ultimately modulate synaptic information transmission between neurons/cells



Fig. 2 Left image (green border) demonstrates an individual performing a double-leg squat in an autonomy supportive environment where they are allowed to choose the double-leg squat exercise. In addition to better neuromuscular control demonstrated by minimal knee valgus in green, dopamine is theorized to be released (blue dots) from the substantia nigra* (medial inferior red cluster) into the ventromedial prefrontal cortex^ (anterior red cluster). The corticostriatal circuit (green arrows) may also facilitate dopamine transmission into regions important for sensorimotor control including but not limited to the primary somatosensory cortex (superior red cluster). Right

image (red border) demonstrates the participant completing the same task but in a controlling environment noted by them thinking about an exercise they wish they could have done. As such, their neuromuscular performance is worse (shown by increased knee valgus in red) and dopamine transmission is limited (no dopamine release/blue dots). *We emphasize that dopamine can also be released from other regions including, but not limited to, the ventral tegmental area. ^Dopamine is also released into other regions including but not limited to the ventromedial striatum

During an ACL injury intervention or even a "camp" to improve sport performance, athletes could have control over their travel-related sleep schedules to support autonomy and be provided perceptually easier criterion regarding the necessary amount of meditation they must complete to enhance their expectancies. While we recognize this likely is not harmful, per say, and was outside the scope of the initial OPTIMAL framework, we emphasize that dopamine must be released while completing the movement that promotes the desired motor learning outcomes, whether that is geared towards general performance or injury resistance. In sum, and in line with our recommendations of more purposeful consideration of how expectancies are enhanced in youth, we also emphasize caution when designing interventions aimed to regulate dopamine in youth, at least until direct supporting neuroscientific data exists for OPTIMAL or OPTIMAL PREP-specific strategies.

Potential Neuroplastic Mechanisms for an External Focus of Attention

An external focus has also been linked to a similar, favorable dopaminergic response to enhanced expectancies and autonomy support due to the immediate performance benefits of an external focus promoting patient self-efficacy [18]. However, dopamine release is likely only a partial contributor to motor performance/learning related to external focus, as attentional allocation is partially independent from the motivational benefits achieved using the other two pillars [240]. Indeed, an external focus is currently the only pillar that has been directly supported using neuroscientific methods within the constraints of OPTIMAL theory [114, 115, 181, 193, 195, 251, 252]. Investigations using transcranial magnetic stimulation have revealed that adopting an external focus relative to an internal focus can elevate intracortical inhibition of the primary motor cortex [115]. Though it is important to note that the supporting literature used attentional focus manipulations during fine motor control movements of isometric finger abduction movements using transcranial magnetic stimulation and electromyography [115], and there could be limitations if attempting to generalize to quadriceps peak force production [144], limiting direct application to ACLR recovery. As previously noted, transcranial magnetic stimulation is limited by its inability to simultaneously quantify CNS dysfunction beyond primary motor cortex, limiting direct application to ACL injuries or OPTIMAL PREP strategies more generally. In light of research utilizing fMRI derived outcomes, and external focus also altering brain activity within numerous, distinct brain regions not limited to the primary motor cortex [181, 251, 252], we propose an expanded neuroplastic mechanism for an external focus that supplements elevated intracortical inhibition of the primary

motor cortex [79] for enhanced application of OPTIMAL PREP strategies.

We hypothesize that the mechanism for an external focus enhancing motor performance/learning may be through enhanced sensorimotor integration that promotes primary motor cortex efficiency (i.e., less brain activity in this region during movement)—concurrent with modulation of intracortical inhibition and corticospinal excitability of this region. For instance, switching from a trained internal focus to an external focus increased activation throughout regions important for sensorimotor control [252] and simply adopting an external focus increased activation in the primary motor cortex and other sensorimotor control regions [251]. Further, these findings were partially replicated in a more recent fMRI study of a gross motor, knee flexion and extension movement [181]. Focusing externally on a visual target promoted increased activation throughout regions important for visual, sensorimotor integration including the lingual gyrus and intracalcarine cortex [181]. In contrast, when participants focused internally on "squeezing their quadriceps" there was increased activity in the primary motor cortex, indicating potentially less efficiency [181]. Future research is needed to inform more definitive conclusions, however the existing studies using fMRI support the positive influence of an external focus on sensorimotor regions to support primary motor cortex efficiency.

Of relevance to ACL injury risk reduction and youth, our hypothesis is also supported by preliminary findings from a six-week, technology-based externally focused injury prevention study that included pre- to post-intervention assessments of knee motor control in high school soccer players (3D motion analysis, virtual reality, and fMRI) [84]. Data indicated pre- to post-intervention increases in visual/sensory/motor planning brain activity during a positioning leg extension task, reduced primary motor cortex brain activity during a loaded leg press task, and decreased hip adduction and knee rotation during a drop vertical jump within a virtual reality soccer scenario [84]. As the respective post-intervention brain activation changes highly correlated with the improvements in landing biomechanics, the authors proposed a mechanism whereby increased sensorimotor integration brain activity supported primary motor cortex efficiency for enhanced landing mechanics during sport [84]. Accordingly, our neurophysiologic hypothesis for external focus within OPTIMAL PREP strategies is in direct, additive alignment with the mechanisms proposed previously to enhance sensory related activation and efficient motor activation secondary to modulation of intracortical inhibition and corticospinal excitability.

In Fig. 3, we visually contrast our neurophysiologic hypothesis for optimizing attentional focus using a balance control exercise while patients following ACLR receive instruction-based augmented feedback (internal and external

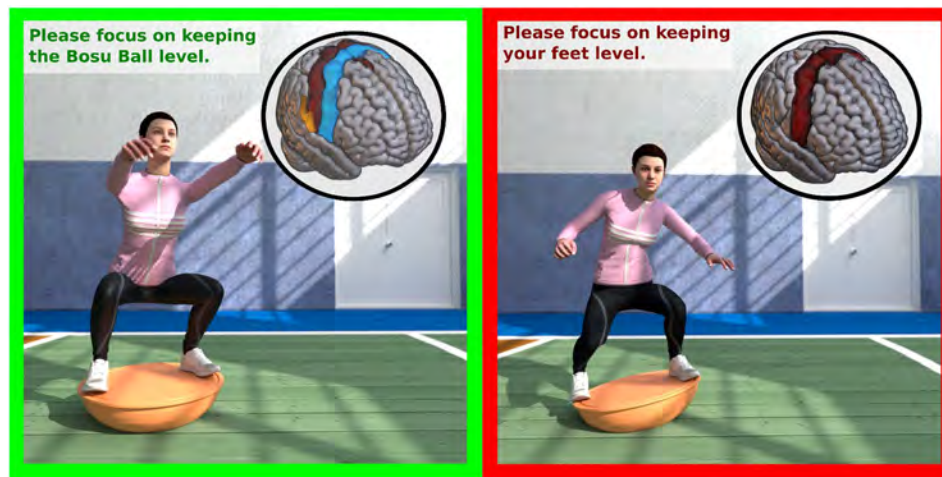


Fig. 3 Left image (green border) demonstrates an individual performing a balance control exercise on a BOSU® ball after receiving instruction based, externally focused feedback. We hypothesize* the better neuromuscular control using an external focus demonstrated by a 'level' BOSU® ball® occurs, in part, due to increased brain activity in regions important for sensorimotor control[^] (post central gyrus, supplementary motor area, and a portion of the secondary somatosensory cortex in yellow/red coloring) that supports reduced or more efficient primary motor cortex[#] activation (colored blue). Right image (red border) demonstrates the participant completing the same task but with instruction-based, internally-focused feedback. As such,

their neuromuscular control is poorer shown by a titled BOSU® ball and excessive trunk lean and activity in the primary motor cortex is no longer efficient/increased activity (colored red) and sensorimotor control regions are not engaged (not colored). *To note, we also hypothesize an external focus to concurrently modulate intracortical inhibition and corticospinal excitability of the primary motor cortex that is not visually displayed. [^]Many other regions are involved in sensorimotor control (including the basal ganglia, pre-motor areas, and many more not colored here). [#]The primary motor cortex is also considered a sensorimotor control region, but is activated secondary to information derived from the surrounding regions

focus). We also reiterate that ACL injury is just provided as an example of how OPTIMAL PREP strategies, such as an external focus, can be effective, but its general application for injury resistance and exercise performance in youth is limitless. We refer the reader to supporting literature [52] that provides instruction-based examples of an external focus for OPTIMAL PREP training application more broadly, and also how technologies of the future could deliver this augmented feedback automatically with minimal practitioner burden.

Potentially Interactive Neuroplastic Mechanisms for Combined Pillars

We discussed the potential neurophysiologic mechanisms underlying the three pillars of the OPTIMAL theory of motor learning and their potential usefulness to target the CNS and motor dysfunction associated with ACL injury. The two motivational factors—enhanced expectancies and autonomy support—were theorized to increase motivation and promote positive dopaminergic responses throughout the cortex to adaptively modulate synaptic information transmission to enhance motor performance, and ultimately motor learning. Further, we hypothesized that focusing externally promotes brain activation in regions important for

sensorimotor control/integration to support primary motor cortex efficiency concurrent with modulation of intracortical inhibition and corticospinal excitability of this region. Albeit these mechanisms may seem somewhat dissimilar between the two motivational factors and attention factor, combined motor performance/learning benefits are possible when OPTIMAL integration of pillars are used additively (relative to single factors), indicating a high degree of neuromechanistic, interacting overlap is likely.

One explanation could be that utilizing all pillars simply activates each proposed neurophysiologic mechanism at once, thereby resulting in rapid brain adaptations. For instance, motivation could trigger the release of dopamine through corticostriatal circuitry in tandem with proliferated engagement of sensorimotor control regions (with some regions plausibly overlapping during this process, such as the basal ganglia). However, another explanation could be that the dopamine boosts from motivation uniquely modulate synaptic information transmission in frontal regions along the mesocortical pathway (e.g., prefrontal cortex) and in parietal regions particularly responsive to an external focus (i.e., sensorimotor control regions), thus facilitating frontoparietal efficiency due to this network's interconnectedness with the motor system [61]. Considered a component of a broader cortical system involved in cognitive "control" [41, 63], the frontoparietal network is heavily involved in

the attentive selection of sensory information and is connected through the superior longitudinal fasciculus (a major white matter pathway) [179]. Preliminary evidence using functional near infrared spectroscopy also implicates the frontoparietal network as a potential neural substrate underlying personalized attentional focus for motor performance/learning [193, 195], but future research is needed, particularly with respect to OPTIMAL PREP training applications for youth and the manner in which the pillars interact more broadly.

Summary, Considerations, and Future Directions

Despite growing excitement for applying OPTIMAL PREP strategies to future training applications, limitations with our proposed framework warrant acknowledgement. Specifically, OPTIMAL theory has been understudied specific to patients with musculoskeletal injuries and divergent findings indicate there is no "one-size-fits all" solution or "law" that improves motor performance/learning in every given scenario; an external focus is generally most effective, but not in all cases [18, 47, 82, 101, 103, 194, 196]. For instance, pathologies that modify the CNS may result in unique amplification or decreased effectiveness of OPTIMAL-derived strategies [18]. Further, unexpected variable combinations have enhanced motor learning in simple, laboratory-based tasks [183], thus unique combination (s) and "dose (s)" of pillar (s) may be superior for promoting desirable movement adaptations when implementing OPTIMAL PREP strategies in realistic and complex training environments. In other words, we emphasize no single pillar—or combination of pillars—is robustly superior, warranting future research to deconstruct how the OPTIMAL pillars interact with individual, task, and environmental constraints to guide PREP application. Despite behavioral support for OPTIMAL PREP strategies to promote motor learning, there is also an over-reliance on shorter duration interventions, warranting the study of long-term interventions and associated dose–response relationships in future research. Likewise, OPTIMAL theory has limited, high-fidelity neuroscientific empirical support, is primarily theoretical, and/or is supported by indirect, cross-sectional CNS evidence [240]. We emphasize that other positive brain adaptations—dependent on the patient population investigated—likely play a supporting, interacting, or additive role for OPTIMAL PREP strategies to promote injury resistance and exercise performance more generally. These neuroplastic changes potentially include connectivity changes within or between numerous other brain networks important for motor learning, alterations to gray matter volume, microstructural alterations to the integrity of white matter tracts, and many more (e.g.

biochemical/cellular processes involving methyl-D-aspartate receptors, glutamate, calcium ions, and second-messenger systems).

The neuroscience of musculoskeletal injury is also in its infancy with continuously evolving paradigms aimed to better simulate neuromechanical demands associated with sports participation [27, 84]. Technological constraints have also limited the collective understanding between gross motor brain function and movement mechanics associated with injury. 3D motion analysis cameras generally contain ferromagnetic material that cannot be used in an MRI environment, however, emergent paradigms and technologies have begun to overcome these limitations, providing novel opportunities for integrated CNS and biomechanical assessments [7, 27]. Lastly, our OPTIMAL PREP framework is intended to be sex-agnostic based on currently known, sex-related factors of neurodevelopment. However, we acknowledge that future research should clarify the interaction of sex-specific motor development on the unique neural response to OPTIMAL PREP. Such future investigation may reveal nuanced, sex-specific findings that could ultimately support more personalized approaches for males and females [56]. Despite these limitations, the heightened CNS plasticity in youth [74, 168, 207, 218] indicates a unique time window to apply OPTIMAL PREP training strategies for desirable motor control. Though potentially amplified effectiveness is possible in the youngest/pre- to early-adolescent age groups based on neuroplasticity [56], we anticipate OPTIMAL PREP to be beneficial across the spectrum of youth age groups through early adulthood.

In conclusion, we are excited for the opportunities to improve injury resistance, enhance exercise performance, and support play in all youth, including those with and without musculoskeletal conditions that affect neuromotor development and control.

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Practical Training Strategies to Apply Neuro-Mechanistic Motor Learning Principles to Facilitate Adaptations Towards Injury-Resistant Movement in Youth

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Abstract

Youth may be particularly responsive to motor learning training strategies that support injury-resistant movement mechanics in youth for prevention programs that reduce injury risk, injury rehabilitation, exercise performance, and play more generally (Optimizing Performance Through Intrinsic Motivation and Attention for Learning Prevention Rehabilitation Exercise Play; OPTIMAL PREP). One purpose of the present manuscript was to provide clinical applications and tangible examples of how to implement the proposed techniques derived from OPTIMAL theory into PREP strategies for youth. A secondary purpose was to review recent advances in technology that support the clinical application of OPTIMAL PREP strategies without extensive resources/programming knowledge to promote evidence-driven tools that will support practitioner feedback delivery. The majority of examples provided are within the context of anterior cruciate ligament (ACL) injury rehabilitation, but we emphasize the potential for OPTIMAL PREP strategies to be applied to a range of populations and training scenarios that will promote injury resistance and keep youth active and healthy.

Keywords Rehabilitation · Prevention · Exercise performance · Technology

Introduction

Participating in sports at an early age is attributed to numerous physical and psychosocial benefits that support long-term neuromotor development [30, 36, 54, 57, 59, 88], with youth being a particularly ideal time period to implement exercise-based interventions [9, 55–58, 60–62, 65, 72, 78]. The OPTIMAL theory of motor learning (Optimizing

Performance Through Intrinsic Motivation and Attention for Learning) [123] proposes three "pillars"—two motivational (enhanced expectancies, autonomy support) and one attentional (external focus of attention)—that may support youth injury prevention strategies (reduction of injury risk), injury rehabilitation, exercise performance, and play more generally (Prevention, Rehabilitation, Exercise, Play; PREP) [24, 25]. Implementation of OPTIMAL PREP training strategies

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is further theorized to promote the long-term retention of injury-resistant motor control by capitalizing youth's heightened central nervous system (CNS) plasticity and potential for neuro-mechanistically-targeted treatments to promote positive neuromotor adaptations [24, 25].

To facilitate the translation of theory to clinical practice, one purpose of the present manuscript is to provide clinical applications and tangible examples of how to implement the proposed OPTIMAL PREP strategies for youth. Historically, these principles have been delivered via verbal augmented feedback or "instruction-based" methods with or without the inclusion of simple visual feedback. An example of this is a cone being placed in front of a patient to focus on and jump towards in an effort to promote an external focus of attention. Prior approaches to feedback delivery has, in part, been due to technological constraints associated with the automated delivery of more complex, augmented biofeedback, as these methods have been limited to expensive laboratory environments and necessitated high levels of expertise, such as visual displays of computer-generated geometric shapes that respond in real-time to patients' movement mechanics (deemed "technology-based" herein). Thus, a secondary purpose of the present manuscript is to review recent advances in technology that support the clinical application of OPTIMAL PREP strategies without extensive resources or programming knowledge to reduce the burden of clinicians providing the most appropriate instruction-based verbal feedback. Throughout the manuscript a brief summary of behavioral literature supporting the application of OPTIMAL theory is provided, but we direct the reader to a more thorough review of the extant literature and definitions of potentially unfamiliar terminology [25]. Of note, we provide most examples within the context of patients following ACL reconstruction (ACLR) and undergoing rehabilitation, but emphasize that OPTIMAL PREP strategies can be applied across the spectrum of youth ages—in both males and females—ranging from pre-adolescence (~6 years of age) to early adulthood (~25 years of age) [24, 25]. Importantly, we emphasize OPTIMAL PREP strategies could also be beneficial for youth with and without musculoskeletal-related conditions and are applicable to a wide range of training scenarios including injury prevention programs for further reduced risk, injury rehabilitation, and exercise performance/general play more broadly [24, 25].

Enhanced Expectancies and Clinical Applications Using Instruction-Based Feedback

Enhancing expectancies refers to boosting an individual's sense of confidence and "expectations to succeed in the future", which, in turn, can better prepare the performer for action. Enhancing patient expectancies can be achieved by using positive/social-comparative feedback, which enhances

conceptions of personal ability and reduces perceived task difficulty [123]. In turn, improved patient self-efficacy, confidence/motivation, and expectation for success can contribute to enhanced motor behavior. Furthermore, enhanced expectancies can even facilitate movement efficiency [104]; this is particularly relevant to ACL injury, as maladaptive (or less efficient) neuromuscular function has been observed [17, 111] and deemed a precursor to secondary injury risk [46, 83]. ACL injury can also lead to fear of (re)injury—the most commonly cited reason among athletes who do not return to play [76]—potentially leading to increased muscular tension, fatigue, decreased coordination, and as a result, higher vulnerability to future injury [3]. As these psychological factors regarding perceived ability are critical for an athlete's successful return to sport [66, 86], it is noteworthy that enhancing expectancies can improve self-efficacy [7, 8] and could potentially reduce fear of (re)injury.

Practitioners, used herein to be inclusive of researchers, clinicians, coaches, instructors, physical therapists, athletic trainers, certified strength and conditioning specialists, teammates, etc., can enhance expectancies within OPTIMAL PREP training applications to promote injury-resistant movement. Specifically, positive feedback can seamlessly be provided following good repetitions or the patient's most effective repetitions (e.g. following the back squat: "Your knee alignment has significantly improved from last week's session"). Likewise, social-comparative feedback is also easily implementable and favorably juxtaposes the patient's current performance with normative performances of others performing the same task. However, this feedback should not be framed in a manner that would allow immediate peers and teammates to become aware of such negative social comparisons, or at least used with caution and with consideration of how it may influence the mindset of a given athlete [24] (e.g., "Your performance on this task is well above average"). Self-modeling can also be achieved using videos where a clinician displays to the patient their previous success, such as a pre-injury video of the patient performing a successful movement during rehabilitation. Self-modeling can also be achieved by providing videos of models who identify to the patient, such as an athlete from the same sport who experienced an injury describing their personal barriers and achievements during pre- and post-operative recovery. For example, self-modeling has been used to promote a current patient's self-efficacy while also reducing pain [63] and can reduce biomechanics associated with ACL injury risk [87].

Lastly, participants' confidence can even be raised by reducing perceptions of task difficulty and/or providing fake positive feedback. However, fake positive feedback must be "purposeful", such that it does not induce a level of confidence that exceeds an individuals' physical capability, potentially exposing them to greater injury risk [24]. For instance,

during a single leg hop a clinician could safely place a cone at a distance perceived as "easy" to reach by the patient to enhance self-efficacy before increasing the perceived distance the patient strives to jump to. As an illustrative example with respect to youth play, instructors could even adopt the "Ebbinghaus Illusion" that can enhance self-efficacy and motor behavior by making targets appear larger than they actually are [7, 8, 19, 82]. For instance, this principle could be used in youth by creating "perceptually larger targets" an athlete must kick a soccer ball towards; small objects could surround a goal target to make it appear larger. Notably, many sports performance examples likely will not induce injury risk, but careful consideration of purposeful expectancies are necessary in many medical scenarios and patient safety should be considered as to not induce a false sense of ability that could increase injury-risk behavior [24]. We provide a few more specific examples within the context of ACL injury rehabilitation in Table 1.

Autonomy Support and Clinical Applications Using Instruction-Based Feedback

Autonomy support refers to providing learners a degree of self-control which can positively influence self-efficacy/motivation to enhance motor performance and learning [20, 49, 52, 99, 116]. Autonomy support can be provided through numerous means, including control over individual practice conditions, instructional feedback that bolsters feelings of self-control, and allowing patients numerous opportunities for choices, with even just one choice potentially being beneficial. Like enhanced expectancies, conditions that support one's need for autonomy can also target neuromuscular activity [47, 48] and potentially serve as an adjunctive therapy for restoration of neuromuscular deficits associated with ACLR [84, 109]. For instance, two studies demonstrated that participants who were allowed to choose when to receive feedback following a series of drop landing tasks exhibited biomechanics associated with reduced ACL injury risk during retention and transfer tests [11, 112].

Practitioners can easily provide individuals with opportunities for control during OPTIMAL PREP scenarios without

compromising daily goals and/or prescribed clinical care. For instance, simply asking individuals the order in which they want to do exercises (e.g., "Do you want to perform the double leg squat or leg extension exercise first?"), allowing them to choose when they receive feedback (e.g., "Please let me know when you would like to receive feedback on your squatting technique"), or providing them opportunities to choose when they rest and/or for how long they rest are all easily implementable methods of providing autonomy support. Practitioners can provide motivation-boosting, autonomy-supportive language rather than negatively perceived controlling statements (e.g., "What exercise would you like to work on next week?" vs. "Your exercise next week will be..."). Likewise, when feedback about mechanics is required to ensure safety during particularly high-risk, dynamic exercises such as unanticipated cutting [69–71, 73], a practitioner can be empathetic with the individual and provide clear, supportive, and detailed feedback with solutions to problems. For instance, "I am continuously impressed by your progress. I understand how challenging these tasks are and would like you to consider practicing a few trials at a slower speed so we can optimize your technique to achieve faster progression," in contrast to "Let's try these tasks again." Lastly, the opportunity for choice can be purposefully provided "incidentally" to not alter the designed care to be provided that day. For instance, a practitioner could ask an individual to select the background music, ask if they would like the temperature of the room changed, or even if there is a color of hand towel they prefer to use while exercising. Such "trivial" or "task-irrelevant" choices may seem like they would not affect motor function, but have been supported by recent literatures [45, 53, 118, 121] and may be particularly beneficial to youth. Trivial and task-irrelevant choices may also be the preferred manipulation for psychologically immature and relatively younger athletes; specifically, for those in controlling environments accustomed and reliant on others for critical decision-making (a 6- vs. 19-year-old athlete) [24]. Perceiving that an athlete made an "incorrect" task-related decision could be distressing for those with less psychological maturity, whereas incidental/trivial choices may be perceived as less important thereby

Table 1 Implementation of enhanced expectancies within existing ACL injury rehabilitation protocols

Existing therapeutic exercise	Category of enhanced expectancies	Implementation of enhanced expectancies
Russian dead lifts	Positive feedback	"You displayed excellent form during your previous set"
T-test agility drill	Social-comparative feedback	"You completed your last repetition considerably faster than the average time for your sport"
Step-ups	Self-modeling	Provide edited video of previous repetitions deemed superior, emphasizing how such improvement has occurred
Single-leg balance	Perceived task difficulty	Initially redefine success and allow the opposing foot to touch-down, then progress to more challenging parameters, keeping pace with the patient's physical capability

alleviating worry during or after the decision-making process. Relatively younger athletes may also have limited experience/expertise in OPTIMAL PREP training modalities, warranting individual consideration when determining what type of autonomy support is provided for a given task or exercise. Specifically, autonomy support should only be provided if it purposefully implemented and appropriately reflects the youth athlete's psychological maturity, experience, technical competency, task-mastery, etc.[24]. Additional autonomy-supportive examples are detailed in Table 2 using ACL injury rehabilitation as an example.

External Focus and Clinical Applications Using Instruction-Based Feedback

The attentional factor of OPTIMAL theory emphasizes the importance of directing an individual's attention externally toward an intended movement effect (i.e., an external focus of attention) compared to body movements (i.e., an internal focus of attention) [122, 123]. The beneficial effects of an external focus on motor behavior have been reported for numerous tasks, skill levels, and populations [117]. Like the motivational pillars, an external focus can also enhance neuromuscular efficiency [110, 120, 125], but relative to the motivational pillars, has far more empirical support for a range of factors important for OPTIMAL PREP strategies, including balance control [26, 27, 50, 85, 96, 124], performance and movement accuracy [92, 95, 125], jump/hop distance [89, 91, 93, 115], and injury-resistant biomechanics [10, 11, 14, 15, 23, 34, 40, 94, 112, 113].

As discussed previously [24], within the context of ACL injury literature, an external focus has been used interchangeably with whether the augmented feedback is provided verbally or visually [6]. Augmented feedback studies have generally shown improved performance and/or biomechanics associated with ACL injury risk when an external focus is provided, whether feedback is delivered verbally/instruction- or visually/technology-based [10, 11, 14, 15, 23, 34, 38, 40, 94, 112, 113, 120]. With respect to verbal instruction, if a practitioner's goal is to enhance performance of a hop or jump (i.e., elicit a further, higher, or quicker jump), instruction could be modified to direct an individual's

attention to performance- or mechanic-specific outcomes [77, 94]. For instance, if the goal is to specifically enhance drop vertical jump height, a cue could be provided to "... focus on getting as close to the ceiling as possible [77]." However, when the goal is to enhance movement mechanics, a practitioner could adhere a piece of tape on the patella and direct the individual to "push the tape" in a direction associated with safer landing mechanics [94]. As another example, while performing a supine "quad set" for the purpose of re-educating the quadriceps and increasing terminal knee extension, the simple instruction "focus on pressing into the table" is likely adequate to create an external focus. Whether practitioners aim to improve performance or injury-resistant biomechanics, they should be mindful that athletes exhibit specific responses to cues given [77, 94], with better performance not always reducing injury risk and vice versa. Thus, judiciously targeting the appropriate movement is critical. To aid practitioners in the implementation of "instruction-based" external focus strategies into OPTIMAL PREP training scenarios, examples using common knee exercises for ACL injury rehabilitation are provided in Table 3.

Furthermore, an external focus can be additively combined with enhanced expectancies and autonomy support for potentially more robust motor learning. We direct the reader to recent literature for more detail [24], but we are simply referring to the utilization of all three pillars during a single training session. A few instruction-based additive examples are presented in Table 4 for how this could be implemented as part of ACL injury rehabilitation.

Technologies of the Future to Integrate OPTIMAL PREP Strategies

While traditional "instruction-based" techniques are supported with empirical evidence to enhance motor performance and learning, recent advances in consumer-grade technologies have provided unique opportunities for integrating OPTIMAL PREP strategies for various training scenarios. Though these technology-based modalities have demonstrated high effectiveness for promoting injury-resistant biomechanics and are often theorized to engage an external focus of attention, they have historically been

Table 2 Implementation of autonomy support within existing ACL injury rehabilitation protocols

Existing therapeutic exercise	Category of autonomy support	Implementation of autonomy support
Hamstring curls	Task-relevant	Allow the patient to choose between the prone curl machine or ankle weights
Gait re-training	Task-relevant	Allow the patient to choose between a clockwise or counterclockwise walk around the clinic
Short-arc quadricep sets	Task-irrelevant	Allow the patient to choose the color of their bolster
Heel slides on wall	Task-irrelevant	Allow the patient to select the wall on which to perform heel slides

Table 3 Implementation of external focus of attention within existing ACL injury rehabilitation protocols

Existing therapeutic exercise	Category of external focus of attention	Implementation of external focus of attention
Forward and lateral lunges	Frequency	Additively including verbal instructions that ask patients to extend past a piece of tape placed on the floor
Clamshell	Distance	Verbally instruct the patient to “Concentrate on reaching for the ceiling”
Gluteal bridging	Direction	Verbally instruct the patient to “Press the floor away”
Plyometric training	Practice variability	Varying barriers, depths, directions, and bases of support

Table 4 Implementation of additive effects within existing ACL injury rehabilitation protocols

Rehabilitation Exercise	Enhanced expectancies component	Autonomy support component	External focus of attention component
Standing hip abduction	“Your control and balance are much better than when you first performed this exercise”	Allow the patient to choose between performing this exercise at the beginning or the end of the rehabilitation session	Verbally instruct the patient to “Focus on extending towards the wall”
Single-leg squat	Emphasizing to the patient their improved endurance and ability to perform more repetitions recently	Allow the patient to choose between performing 3 sets of 10 repetitions or 2 sets of 15 repetitions	Verbally instruct the patient to “Focus on pressing into the floor”

constrained to expensive biomechanics laboratories and necessitate the user to have expertise of several different tools and systems (e.g., motion capture systems, augmented reality, computer programming, etc.) [13–15, 31, 32, 35]. However, and of high relevance for OPTIMAL PREP training applications, rapidly evolving improvements in motion capture and display equipment have drastically reduced costs, increased availability, and enhanced user experiences in terms of quality (e.g., higher screen resolution, faster frame rates, immersive renderings and do not necessitate high levels of expertise. Thus, integrating OPTIMAL PREP strategies with such technology may be particularly useful to practitioners who may feel overwhelmed trying to adhere to the proposed modifications to instructional feedback such that they can let the technology assist with feedback delivery. As clinicians and researchers may be unfamiliar with some of the technology-related terms we use below, a brief reference guide with descriptions is provided in Table 5.

Augmented and Virtual Reality

With the increased availability of augmented and virtual reality technology to consumers, a wide range of software and hardware tools have become available to researchers and clinicians. Many of these tools often have freeware or open-source versions available for researchers and non-profits. For example, the Unity game engine (Unity Technologies; CA, USA) is a popular and easy-to-use software environment for creating augmented and virtual reality content. Additionally, for inexperienced users, there are many free tutorials available online for Unity and other

game development platforms (e.g., Unreal Engine; Epic Games, Inc.; NC, USA). *Unity Free*, available at no cost during the time of this article’s publication, can be used to create interactive 3D environments with complete experimental control that is not often possible in traditional laboratory and ‘real-world’ settings. In terms of research, augmented and virtual realities offer advantages over traditional sports medicine experiments conducted in pristine laboratory settings. For example, stimuli—such as a non-player character that a participant must avoid contact with—can be presented with precise timing to ensure exactly the same experience across participants; alternatively, achieving this without enhanced realities would be momentarily difficult due to the ever present variability in human motor behavior/learning [21, 97].

For rehabilitation and research applications, audio-visual stimuli—developed in programs like Unity—can be presented using a range of different head mounted displays to produce controlled experiences, which both mimic and extend real sports scenarios. For example, youth athletes’ lower extremity biomechanics were evaluated using a virtual soccer environment that provided a realistic, but controlled, jump-landing task that evoked context-specific movement patterns that were specific to soccer, while allowing for comprehensive motion analysis that would not have been possible on the field [22, 40]. For this type of application, when a fully immersive environment is desirable, virtual reality head-mounted displays such as the HTC Vive Pro Eye (HTC Corporation; TW, China), which also offers a built in and affordable eye tracking capabilities, may be appropriate. The Vive and similar head-mounted displays will remove the

Table 5 Reference table of technology-related terminology

Term	Description
Motion capture system	Usually, a system comprised of reflective markers that are attached to participants' bodies and an array of cameras that track the location of the markers that is used to digitize the movement of people
Head mounted display	Typically, a small wearable device that one places over the face. Within the device is display and optics, used to show a virtual environment
Software development kit	A package of software development tools (e.g., libraries, documentation, compilers, and debuggers) that aid and allow developers to create software applications for a specific hardware platform
Avatar and non-player character	An avatar is a virtual representation of an individual's body that is controllable through an input device (e.g., a handheld controller or motion capture system). An NPC is a character that is controlled through software only, with no player input
Virtual reality	Simulated experience or environment, usually including 3D visuals, that is often constructed for the purpose of training or entertainment
Augmented reality	Simulated immersive experience that combines computer generated 3d objects with the real-world environment
Markerless motion capture	Technique that does not rely on tracking markers in order to digitize the movement of people
Game engine	A software-development tool designed to enable the production of video games and augmented/virtual reality applications
Eye tracking	Technique used to measure what or where a person is looking. A camera is often placed externally (e.g., on a pair of glasses) that can track pupil movement
Immersion	The sense of being deeply engaged with a virtual reality environment or virtual task
Light detection and ranging	Technique that utilizes light to measure the distance of surfaces from the sensor. It can be used to create virtual representations of real-world objects
Graphics processing unit	Specialized piece of computer equipment that is utilized to accelerate the creation of digital images. A GPU can also be used to efficiently train and deploy machine learning algorithms
Hologram	Specially generated 3d light field that creates an image which retains the depth, parallax, and other properties of the original object
Inverse kinematic solvers	Defined as the problem of determining a set of appropriate joint configurations based on a known (or desired) position of the feet. Inverse kinematic solvers calculate the positions of arms or legs of avatars and NPCs

external visual field and thereby allow the subject to focus fully on the virtual task at hand.

Alternatively, a specific application may require seamless integration of the task with real-world objects or individuals. In this case, the use of a head-mounted augmented reality device, such as the Microsoft HoloLens (Microsoft Corporation; WA, USA), may be desirable. The HoloLens allows for 3D objects to be displayed in holographic form while also providing built in tracking of the user's hands and eyes. Due to the holographic presentation, the HoloLens allows for a participant to maintain awareness of their surroundings, which can be essential if the task at hand cannot be performed in isolation from other individuals or real-world obstacles. While augmented reality has not been used extensively in sports medicine, one recent study demonstrates that its potential use in clinical settings is promising. A HoloLens was used to create an augmented reality-based task that simulated the movement patterns of game-specific spike jump in volleyball, which effectively elicited similar biomechanics to that of a competitive environment [2]. Importantly, using a wireless augmented reality device in this case allowed training to be performed in a crowded gym environment as participants are able to maintain awareness of their surrounding while receiving feedback relative to virtual

reality. In fact a HoloLens is also being utilized as part of an ongoing clinical trial (clinicaltrials.gov; NCT# 02933008) to institute a program of neuromuscular training, driven by augmented reality feedback to modify youth athletes' biomechanics associated with ACL injury risk [13–15]. In general, both augmented and virtual reality technologies can be used to great effect when combined with other emerging technologies. For example, the addition of markerless motion capture technologies and other tracking devices, described below, can easily allow for virtual representations of subjects (i.e. avatars) to be displayed and manipulated. Avatars add immersion to virtual scenarios and provide visual grounding for subjects to produce natural movement [102].

Despite the limitless potential for augmented and virtual realities, we carefully point out that, for the foreseeable future, these technologies may be limited to one-on-one utilization in the clinic, with limitations for the simultaneous application to groups of players during team-based practices or competitions. Current augmented realities designed to reduce ACL injury risk require kinematic and kinetic data to stream in near "real-time" to support an interactive visual stimulus (i.e., a geometric rectangle) that distorts as a function of an athlete's injury-risk and injury-resistant biomechanics elicited during exercises [13–15, 23, 40]. However,

current marker-based motion capture systems limit the real time joint biomechanical analysis to a single subject, precluding the accommodation of multiple athletes in a training session simultaneously.

Markerless Motion Capture

Current clinical and research applications often leverage multi-camera optical motion capture systems that provide high precision in biomechanical assessment, but these systems may cost a considerable amount, can be difficult to re-configure, and require visible markers to be placed on the subject. Consequently, these systems may not fit within the budget or the available space and expertise of some smaller organizations. They may also be less than ideal for applications that require motion capture to be performed in a mobile setting, for example, at the home of a patient or participant. Recently, markerless motion capture solutions have emerged that capitalize on the significant advancements in machine learning and computing hardware [44, 106]. Two promising examples are the Microsoft Azure Kinect (Microsoft Corporation; WA, USA) and the Apple iPad Pro (Apple Inc.; CA, USA). The Azure Kinect is the newest in a line of small, camera-based devices that can enable motion capture when paired with a high-end desktop computer or laptop. Microsoft also provides multiple software development kits that enable developers to leverage their graphics processing unit-based machine learning tool for 3D joint center estimation. Joint center data derived in this way can then easily be analyzed or used to drive a real-time training or rehabilitation program, such as one of the augmented and virtual reality applications described above. The iPad Pro offers an interesting mix of motion capture and display technology. Recently, a light detection and ranging sensor was added to the newest iPad model, which enables high-precision 3D motion capture and environment mapping. Although it has not been tested for clinical applications, this could offer a very streamlined method of both collecting and displaying motion capture data.

Lastly, the Vive tracker (HTC Corporation; TW, China) is another piece of motion capture equipment that has shown promise in measuring joint rotations and positions with research-grade accuracy and low latency (near real time; ~5 ms) [18, 103]. The Vive tracker is part of a larger Vive system that includes up to four infrared-emitting base stations, two handheld controllers, a head-mounted display, and a small tracker “puck.” With concurrent use of the system’s tracking and display equipment, realistic feedback about a user’s movements can be reflected in real time in the virtual environment. While precise full body kinematic motion capture—as provided by systems like the Kinect—is not possible without using one Vive tracker for each tracked body segment, a small number

of Vive trackers can be used in conjunction with machine learning to approximate full-body tracking. One example of such implementation would be using the Vive trackers in concert with the Vive Pro head-mounted display and two Vive controllers to approximate full-body tracking. In this scenario, Vive trackers would be placed on the feet and waist, the controllers would track hand positions, and the head-mounted display would provide head tracking. Additionally, software based inverse kinematic solvers can be utilized to transform the tracking data from such a setup into a realistic full-body avatar. Again, this may not be appropriate when highly detailed motion capture recordings are required, but will provide the most frictionless path to full-body motion tracking and avatar presentation.

Eye Tracking

In addition to the potential uses of the Vive head-mounted display and trackers, eye tracking is also possible with the use of a Vive Pro Eye (HTC Corporation; TW, China). Specifically, eye tracking via the Vive Pro Eye can be used as a supplementary tool to investigate how participants visually explore virtual environments. From a research perspective, this tool could even help elucidate the potential role of vision with respect to the attentional focus pillar – where there is an ongoing debate whether an external focus necessitates a person “looking” at the appropriate stimuli [1, 67, 90]. Eye tracking may also be particularly useful to investigate the visual-spatial processing deficits associated with musculoskeletal injury [5, 28, 37, 39, 41, 42, 75, 105, 114]. Based on fMRI data of knee flexion and extension movements [41, 42], researchers have theorized a framework whereby patients rely more heavily on visual-spatial information for knee motor control following ACLR [39] and prospective data indicate reduced visual memory and processing ability also increased primary ACL injury risk [105]. As such, eye tracking could be used to quantify the visual-spatial search strategies patients utilize during ACL injury rehabilitation or for youth with a wide range of musculoskeletal-disorders potentially influenced by altered sensorimotor control strategies. Further, even in the absence of augmented or virtual reality technologies, eye tracking could be used to supplement novel, neurocognitive-based return-to-play paradigms that have been designed to supplement traditional testing in light of neuroplasticity, such as neurocognitive challenges added to traditional hop testing [101]. Eye tracking could simply be used to quantify adherence to manipulations that direct vision, or as an exploratory variable that may be mediating/modulating the effects of a manipulation or intervention across the spectrum of youth populations.

Opportunities to Integrate Instruction-Based Feedback with Emergent Technologies for Optimized Motor Learning: The Future of Exercise Performance

While the technology and research applications just described are not directly related to the OPTIMAL theory of motor learning, a salubrious opportunity exists to combine with enhanced expectancies, autonomy support, and an external focus of attention. Recently developed technological innovations have the potential to create highly effective PREP methods for near limitless training applications. One opportunity for creating new training programs exist by specifically directing a patient's attention externally towards augmented or virtual reality stimuli. However, in place of verbal instruction that must be continuously provided by a practitioner and thus increases staffing resources, a computer program could instruct an individual to keep a horizontal virtual line—displayed within a head mounted-display using

two Vive trackers—to elicit an external focus of attention (see Fig. 1). This provides several advantages as individuals can easily focus their attention towards the display (and concurrently their own performance) without looking down at their feet (BOSU® ball in this example), which detracts from proper form and execution on the task [68]. Additionally, performance can be easily quantified through the recorded positional data of the Vive trackers. This data may be used to quantify individual training session performance or potentially progression throughout rehabilitation. While this is only one specific example of how external focus and technology can be combined, there are numerous opportunities—from rehabilitation after a spinal cord injury [81] to baseball pitch training [108]—for integrating technological advancements with OPTIMAL PREP strategies.

The ability to quantify performance across individual training sessions provides excellent opportunities for further integrating enhanced expectancies and autonomy support into any technology-based training program. For instance, a

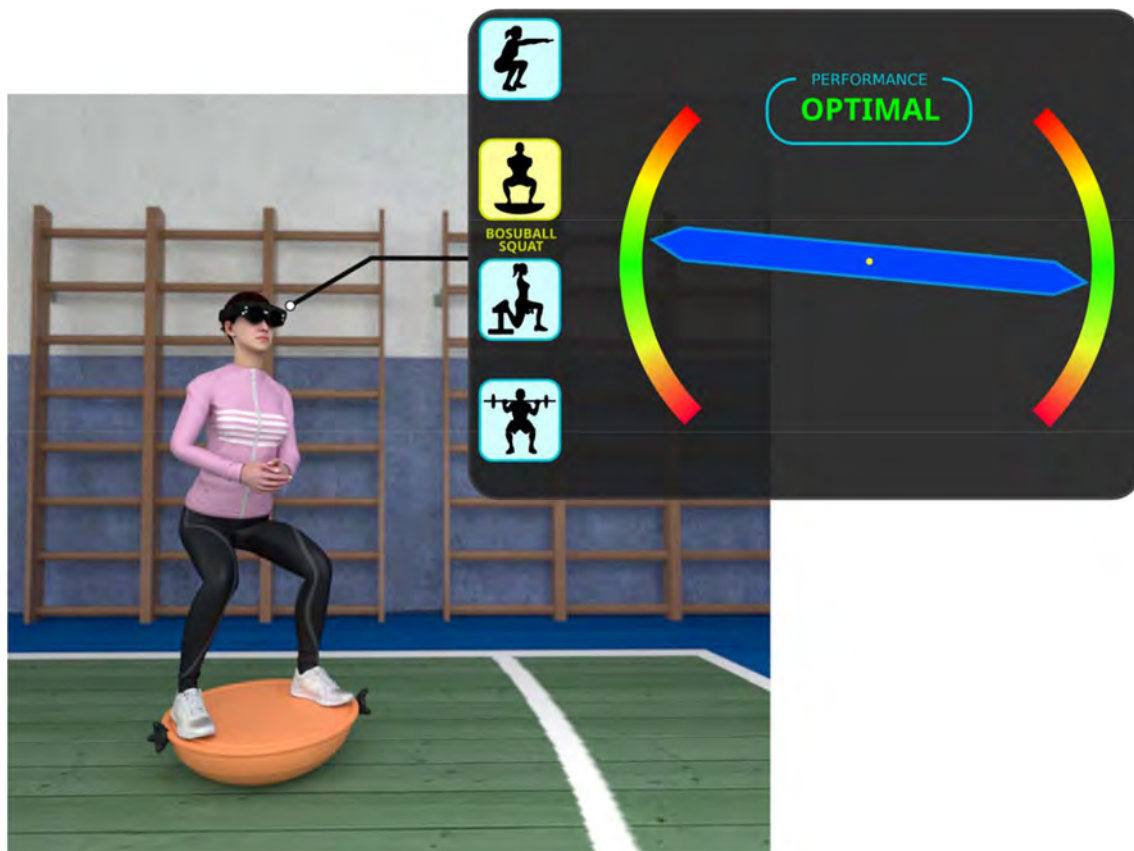


Fig. 1 Image demonstrates an approach to integrate all three pillars of OPTIMAL theory during a training session. Specifically, this individual is being provided feedback through a virtual reality headset while performing squats on a BOSU® ball. Importantly, the participant is provided with four choices of exercises to promote autonomy support (BOSU® ball exercise colored yellow; other three exercises shaded blue indicating they were not chosen). A blue colored bar provides

biofeedback via a level indicator streamed in near real-time by the black sensors attached to the BOSU ball that an individual can attend to for promoting an external focus. The blue feedback bar can also be positively biased with largely green and yellow colors indicating good performance to enhance purposeful expectancies (the program could restrict the bar moving into the "red" as a function of individual physical capability while maintaining their safety)

practitioner could easily modify the stimulus to only provide purposeful feedback to enhance expectancies of individuals, safely (colored green in Fig. 1). For instance, positive feedback could be provided that challenges the individual without extending past their physical capability. As such, the practitioner is not required to provide the purposeful feedback, rather the technology would do this automatically and could be systematically programmed to not exceed an individual's constraints. Furthermore, autonomy support—specifically allowing participants choice in training programs—can easily be achieved by providing a "gamification" of the individual session via technology. Gamification is the process of incorporating game features like social interaction, rules and goals, and control into traditionally nongame settings, such as classrooms, in order to increase the outcomes and effectiveness of training programs [33, 51, 126]. While practically all sports related activities inherently possess at least one gaming element, current rehabilitation and injury prevention/risk reduction strategies are specific areas that could benefit from increased gamification integrated into current practice. Gamification may be particularly beneficial in youth injury rehabilitation programs following the cessation of sport participation as motivation, autonomy, and numerous other psychological factors are impaired during recovery [107]. Moreover, there is a substantial body of literature that indicates gamification can increase motivation levels and engagement with learning programs while improving learning outcomes [33, 126]. However, gamification may be more appealing to relatively younger or psychologically immature athletes who require additional stimuli to maintain cognitive engagement. In contrast, some relatively older youth may have more exposure to video/computer games, cell phone games, etc., thus gamification may be particularly beneficial for these athletes. Though future research is needed, age and psychological maturity should be carefully considered before gamification is employed. Likewise, age and psychological-related factors should always be considered before any of the other aforementioned technologies or strategies are implemented with OPTIMAL PREP.

Despite the lack of empirical support for gamification of rehabilitation and injury prevention programs within sports medicine, there are opportunities to incorporate features of games to similarly increase motor learning and training outcomes. For instance, and as seen in Fig. 1, the individual chose the BOSU® Ball exercise (highlighted yellow), with other exercises that were not selected still displayed, but shaded blue/gray (indicating the individual did not choose those). Likewise, the "gamification" of feedback provided to users—provided either before, during, and/or after an exercise—can be systematically programmed in light of scientific findings (or manipulated/tailored to individual progression). The timing of feedback is a key component of OPTIMAL theory and successful motor learning in

general [64]. Thus, the technological opportunities to not only program what feedback is provided, but when feedback is delivered via PREP strategies can further mitigate practitioner burden. While the timing (prior to, real-time or after exercise) of feedback is important, strategic implementation of OPTIMAL PREP should consider a number of factors such as the desired outcome, the task itself, and individual/environmental constraints, warranting future research. A general consensus is that a trainee should not become "dependent" on feedback—whether that feedback is provided prior to, during, or after a movement and how much is actually delivered—the specific nuances of when to provide feedback and exactly how much is outside the scope of this commentary. However we direct the reader to existing literature on this topic that can provide guidance on this topic [4, 43, 80, 98, 100, 119], and is a promising avenue for future OPTIMAL PREP research. Lastly, the advantages of integrating technology with OPTIMAL PREP strategies extend beyond the benefits provided to the user. With the lower cost of these potential systems and continued expansion of telehealth [29], it is reasonable to expect that a portion of training scenarios will take place away from a clinic or specialized training facility. Integrating technology—specifically the ability to remotely access objective data acquired by the devices—will allow practitioners to monitor progression throughout training and appropriately adjust it based on objective, quantified data.

Summary and Future Directions

In addition to the limitations noted in previous OPTIMAL PREP literature [24, 25], limitations of the practical applications proposed warrant discussion. Firstly, some of our instruction-based examples use tasks that have not been empirically studied for every youth population, age range, and/or training scenario, precluding conclusive insight into the potential widespread effectiveness of OPTIMAL PREP strategies. However, the extant motor learning literature in numerous related populations, ages, and tasks [123] supports the opportunity for all three pillars to be effective for youth injury resistance and exercise performance. Secondly, while relatively uncommon, some individuals may experience cyber sickness with aspects of technology-based approaches, such as while interacting with virtual reality environments; hypothesized to arise from sensory conflicts involving afferent signals from the visual, vestibular, and somatic systems [12, 16, 79]. However, the likelihood of cyber sickness can be reduced by having the visual field correspond in a one-to-one fashion to individual movements [74]. Lastly, our proposed technologies of the future, while more accessible than those prior, are not completely free of resources or technical expertise. Indeed, current and emergent technologies will

continue to require an appropriate level of technical competency and familiarity with a given technology, particularly if practitioners aim to synchronize multiple devices, utilize 'real-time' data streaming, and/or implement research-grade protocols utilizing in-house programming. Fortunately, there are many free online tutorials that practitioners could complete to achieve higher technical competency and more technological familiarity. Furthermore, extensive programming knowledge may not be needed, or only to a very basic extent, as numerous openly accessible platforms for code-share (e.g., Github, Gitlab) and data-share (e.g, Figshare, Dryad, Zenodo) have emerged.

Despite currently known limitations, we have proposed a conceptual framework for the application of OPTIMAL PREP training strategies in youth [24, 25]. Importantly, we do not suggest traditional training methods such as strength training principles be superseded, rather highlight their potential for enhancement through the additive inclusion of the pillars supporting OPTIMAL PREP. Traditional, contemporary, and emergent injury management and exercise performance programs, with any level of current effectiveness, could potentially benefit from incorporating "instruction-based" recommendations and/or future technologies without a significant disruption to their current approaches. Despite minimal widespread clinical implementation, we anticipate future research to further deconstruct the manner in which OPTIMAL PREP strategies may interact with other important training-related variables for injury resistance, such as loading/periodization, psychological factors, and/or age-related factors associated with general physical, emotional, and psychological maturity. In summary, we are excited for the future applications of OPTIMAL PREP training strategies whereby clinicians and researchers work together to support an active, healthy, and injury-resistant lifestyle across the spectrum of youth populations, in both males and females.

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