Update on Proprioception
Considerations for Dance Education

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Abstract

Proprioception is a topic of interest within the larger scope of dance pedagogy, science, and rehabilitation. As the science of proprioception changes, approaches to proprioceptive training also change. Thus, proprioceptive training in dance medicine has expanded to include balance protocols. A key concept within these protocols for treatment of lower extremity injuries is perturbation. Perturbation training is designed to evoke focal neuromuscular control at injured joint sites, as well as more global postural responses for overall balance and coordination. This article provides an update on the science of proprioception within the framework of postural control and balance. Specific practices from rehabilitation that integrate balance exercises into proprioceptive training are considered. Further research is needed to test the efficacy and utility of these exercises within the context of the dance studio.

Proprioception is the sense of body motion—the ability to feel the body moving in space. Despite centuries of scientific interest, the role of proprioception in the organization and execution of movement remains conjectural. In 1906, neurophysiologist Sir Charles Sherrington coined the term proprioception from the Latin "proprius," meaning "one's own," for sensory information derived from neural receptors embedded in joints, muscles, and tendons.[1] These specialized sensory ("afferent") nerve endings are stimulated by body motion and position, providing the body with an awareness of itself and of its location in space. Today, considerable discrepancies persist as to the exact usage and meaning of proprioception and its kindred term kinesthesia.[2] As a sensory system, proprioception includes conscious and non-conscious inter- and extra-personal sensations of static position and movement within the context of a specific environment and task.[3,4] Static position sense incorporates body orientation and body part relationships, while movement sense incorporates neuromuscular and mechanical feedback about the rate, amplitude, direction, and force of movement.[3] Proprioception also contributes to complex neuromuscular processes that underlie postural control and balance, allowing the body to remain oriented and stable in all activities, static and dynamic.[5,6]

Proprioception "drills" are part of comprehensive neuromuscular training (along with flexibility, strengthening, and agility exercises) for prevention and rehabilitation of lower extremity injuries.[3,7] Once characterized by simple exercises of position sense (e.g., timed standing on one leg with eyes closed), proprioceptive exercises now are embedded in expanded balance protocols.[8-10] A key principle in balance testing and training is perturbation, in which graded, controlled forces are applied across injured joints to selectively "destabilize" them while avoiding further risk of injury.[9,11] Careful, selective destabilization is designed to evoke timely, reflexive neuromuscular responses.[9] Additionally, destabilization strategies activate higher neural centers so that postural synergies are also evoked. In these synergies, large groups of muscles respond quickly throughout the whole body to maintain balance (center of mass over the base of support).[12] Perturbation challenges have been shown in rehabilitation to improve balance after lower extremity injury, implying that improvements in proprioception may be an indirect benefit.[13] What follows is a review of the current science of proprioception, presented with a view to considering the potential merits of proprioceptive exercises in dance training.

Although beyond the scope of this review, readers might consider proprioception not only through the lens of science, but also through phenomenology and somatic education, especially in view of the evolving science of embodiment.[14] Because body

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perception and attunement function as both process and product in dance, the phenomenological perspective of the "lived body" helps avoid reductionist thinking in which proprioception is viewed only as a neurophysiological construct.[15] Montero argues that we don't *have* proprioception, we "proprioceive."[16] Reynolds expands on the role of kinesthesia, stating that dancers refine kinesthetic sensation to convey the subtle nuances of movement texture, as well as to transcend the conventions of bodily habit.[17] Our familiar and confident selves are bound up with habitual, normative effort.[17] Embedded within the proprioceptive sense are sensations of muscle tonus and perceptions of heaviness and effort (or effortlessness).[18,19] Proprioception not only helps us know where we are, but also defines perceived effort within environmental and task contexts.[3] The "task" of dancing involves kinesthetic exploration of various movement efforts in which the boundaries of self-to-self and self-to-audience are stretched, and the normative, habitual ways of deliberately using energy are altered.[16]

Neurophysiology: A Brief Glimpse

Proprioceptive input derives from a number of peripheral sensory end organs embedded in muscles, tendons, and articular joint complexes, including ligaments, fascia, and skin.[20,21] The term "somatosensory" better captures the scope of these combined stimuli (musculotendinous, joint, and cutaneous) coming from the body itself and its responses to the environment.[4] Somatosensory input combines with visual and vestibular information to support balance, accounting for 70% of postural control in quiet upright standing.[22] Receptors from muscles, tendons, and joints proper are called "mechanoreceptors." Mechanoreceptors fire in response to mechanical stimuli coming from static position (body orientation) or movement (force, speed, amplitude, and direction). Traditionally, these receptors are classified as muscle spindles (Ia and II fibers), Golgi tendon organs (GTOs) and joint afferents (GTOs, Ruffini endings, Pacinian corpuscles, and free nerve endings).[23] Proprioceptive nerve endings are activated when tissue deforms by way of static positioning or movement, either actual (physically executed or passively manipulated) or imagined. Stimulus modalities include pressure, stretch or rate of change of muscle length, muscular tension and relaxation, as well as vibration and other less clearly defined sources.[23,24] Transduction of neural signals provides a sense of localized position as well as movement, signaling the amount and velocity of joint loading and the degree of muscle length and force. Theoretically, stimulating joint mechanoreceptors increases gamma motor activity, resulting in an increase in the sensitivity of muscle spindles in those muscles surrounding the joint.[24] Increased spindle sensitivity fosters a higher state of "readiness" of the muscle to respond to perturbing forces.[24]

Although it is not practical to consider each individual receptor's isolated contribution to motor programming, Table 1 illustrates the classical schema of neurons. The Roman numerals refer to the afferent nerves' diameters, the size of which influences conduction velocity, the level of threshold firing, and the adaptive properties (how quickly or slowly the nerves respond to deformation resulting in reflex neuromuscular responses). Nerve detection thresholds, for example, usually are lowered (more rapidly responsive) in conditioned muscles[2] and raised (slower to respond) in fatigued muscles.[25]

Proprioceptive or "kinesthetic" awareness results from complex mediation of input distributed throughout all levels of the central nervous system (reflex, brainstem, and higher subcortical and cortical levels).[23,26] Peripheral input from these sensory nerve endings enters into the spinal cord, mediating reflex spinal control at various spinal segments. As input ascends to supraspinal levels, synapses occur throughout the neuraxis, including the cerebellum, brainstem, subcortical (e.g., basal ganglia and thalamus), and cortical (e.g., sensorimotor and association) areas, to mediate more complex levels of motor control.[21] At the reflex level, for example, knee sensory receptors convey non-conscious information about joint loading to the spinal cord through reflex arcs that trigger rapid response of the muscles to contract for timely neuromuscular coordination.[26,27] At higher levels of integration (e.g., brainstem) afferent neurons synapse with visual and vestibular input throughout the neuraxis to facilitate automatic postural control and locomotion. Continual processing of sensory input at the non-conscious level between neurons in the spinal cord, cerebellum, and brainstem underscores the more automatic aspects of balance in both pedestrian and skilled movement.[6,20,21] Integration of sensory input in the somato-sensory cortex (S1, S2, S3, and association areas) aids in elaboration of the body image and body schema.[6,28] Flexible and adaptive body "maps" within the motor program offer a conscious and non-conscious sense of body ownership (of body parts and their locations) and agency (control of body action).[28]

With the developments in technology and sensory neurophysiology in the late 1980s and 1990s the focus of research has shifted from the relative contribution of any one receptor to a more dynamical systems-based approach.[29,30] Scientists have replaced a strict division between afferent (incoming) and efferent (outgoing) neural processing with an integrated, multimodal perspective in which perception and action are intimately coupled and inseparable.[29-31] Explanations of physiological function of sensory phenomena alone do not sufficiently explain how these receptor properties lead to improved behavior or function, making it difficult for dancers to glean practical information from the receptor level to use for training. Instead, proprioception can be viewed within the larger context of interacting constraints on postural control and balance.[29] Maintaining balance within an ever-changing environment requires rapid postural responses to perturbations, both internal (self-induced) and external (gravitational, inertial, and so forth). Examples of internal perturbations include purposely lifting your arms in a port de bras or automatically reaching for a drink while engaged in reading. External perturbations typically involve slipping or tripping.[32] These responses are both anticipatory

Table 1 Sensory Receptors for Proprioception

Receptor	Axon Size	Class	Shape	Location	Firing Threshold & Deformation Source	Adaptive Properties & Effect
Musculotendinous						
Muscle Spindles Intrafusal Fibers	Large myelinated*	Ia	Fusiform "Bag"	Scattered distribution, 3-10 fibers in parallel with 1 extrafusal muscle fiber‡	Low, quick stretch and maintained (tonic) stretch	Velocity-sensitive rapid changes in muscle length†
	Medium myelinated	II	Fusiform "Chain"	In parallel with extrafusal muscle fibers‡	Higher than Ia Tonic stretch	Slow-adapting, static or sustained muscle lengths
Golgi tendon organs (GTOs)	Large myelinated	Ib	Capsular	In series with 1 GTO per 10-20 collagen fibers of tendon	Low, < 1gm tendon tension, active contraction mainly	Accurate sampling of active muscle tension and velocity of change of tension, less responsive to passive stretch
Joint Afferents						
GTOs		Ib		Joint ligaments	Low, Similar to GTOs in tendons, signal tension changes	Slow-adapting
Pacinian Corpuscle	Medium myelinated	II	Onion-shaped, concentric layers	Deep layer joint capusules	Very low, movement, not constant joint position	Rapidly-adapting, high sensitivity to vibration & tissue displacement
Ruffini Endings	Medium myelinated	III	Spindle-shaped capsular	Deep layers in skin, joint capsules, ligaments, tendons	Higher than I, extremes of joint range, passive more than active	Slow-adapting§
Free Nerve Endings	Small, myelinated	IV (Adelta & C)	Branching, non-capsular	Superficial layers of skin, joint capsule	Variable, highly context-dependent	Tissue damage, coarse touch, pain‖

*Neural diameter (large, small) and myelination is significant in conduction velocity. The larger, myelinated fibers conduct faster. †Intrafusal fibers do not add appreciably to the force of muscle contraction, but change in their tension level via the gamma motor system and impact significantly on their sensitivity to muscle length changes.[23] ‡The ratio of muscle spindles to muscle fibers varies with the type of muscle. Larger muscles that generate coarser movements (e.g., superficial back muscles) have fewer spindles compared with extraocular muscles or intrinsics of the hand that require greater sensitivity and accuracy for precise movements of the hand and for manipulation, respectively.[23] §While not much is understood about joint afferents (which also occur in skin), Pacinian and Ruffini afferents presumably respond to tracking of motion and position (of fingers), while Merkel cell afferents and Meissner corpuscles (which appear only in skin) are more responsive to shape and pattern detail, as evidenced in research on Braille readers' finger afferents, providing "stereognosis." ‖Note that with any abnormal (repetitive, continuous, overly-forceful) input, any receptor can become a "nociceptor" and signal pain.

and reactive, and occur much faster than the fastest voluntary movements.[33] A neuromotor state of "readiness" acts to prime postural response synergies both in anticipation and in response to modifications in the motor program or the environment.[33] Integrated proprioceptive input at all levels of the nervous system functions to organize body stability ahead of movement execution (feedforward) as well as to correct for velocity and timing errors (feedback). A simple example is that as you descend a staircase your foot "knows" there is a step below it, how far it is located below the descending body, and how much control is needed to descend without losing your balance, even with eyes closed. This information is vital to dancers who learn not only how to self-correct seamlessly for errors in space, time, or effort as they move, but also how to anticipate effort values in advance of the onset and execution of movement. Training these rapidly adaptive postural responses requires a specialized approach in which perturbation plays a key role (discussed below).

Proprioceptive responsiveness is readily altered, adapting to a number of factors including postural habit, conditioning, and movement training. Factors leading to *diminished* (hypotonic) or *inappropriately exaggerated* (hypertonic) proprioceptive responses include: 1. prolonged periods where muscles are held in shortened (i.e., unloaded or un-stretched positions) or in overly stretched lengths, as is commonly seen in habitual postural malalignment[34]; 2. prolonged or repetitive maximum voluntary contractions without sufficient rest between repetitions[25]; 3. musculoskeletal injury and surgical interventions, especially with inadequate or incomplete rehabilitation[19]; and 4. joint degeneration or other neuromuscular disease.[35] The sensitivity of proprioceptors also is altered throughout the lifespan by a variety of other factors, including gender,[36] development,[37] menstruation and other hormonal fluctuations during key growth periods,[38] nutrition and weight loss or gain,[39] vitamin B6 toxicity and exposure to industrial pollutants,[40] steroid use and bodybuilding,[41] declines associated with aging or prolonged immobility at any age,[35] emotional stress,[42] and even shifting attentional states.[43]

Proprioception: A Dancer's Advantage?

A healthy, responsive proprioceptive system appears integral to the way dancers monitor themselves, learn, and self-correct, implying a potential advantage in motor planning, motor control, and postural stability.[44] Presumably, professional dance training strengthens the accuracy of proprioceptive inputs and shifts sensorimotor dominance from vision to a more internally-based system of reference.[45] This would suggest that dancers develop an augmented inner body sense compared to non-dancers, or that those persons who are what Howard Gardner calls "kinesthetic thinkers" gravitate toward careers in dance.[46] Dancers demonstrate increased accuracy of position-matching when tested against gymnasts and untrained controls, both in static[47] and dynamic testing.[48] Results from research on balance, however, indicate that dancers do not necessarily have an advantage over other populations or under all conditions. Researchers suggest that: 1. ballet training alone without concurrent additional coordination training does not lead to improvements in ankle joint position sense or positive post-rehabilitation measures of balance[49]; 2. trained dancers exhibit perceptual and balance errors in posturography testing with EMG[50]; 3. dancers perform less well on balance outcome measures compared to judo practitioners[51]; and 4. professional dancers perform less well on platform posturography testing during eyes-closed conditions that demand increased proprioceptive strategies for balance as the base of support is narrowed and vision is occluded.[52] While proprioceptive training is routine in dance rehabilitation, few reports exist on the effects of targeted proprioception exercises on dance technique, except perhaps with children.[53] Even a simple exercise such as balancing in passé relevé with eyes closed is rarely performed in adult dance training.

Injury

For a dancer, a simple ankle sprain is a whole body injury. A proprioceptive deficit, however minimal, compromises finely tuned postural control, jeopardizing balance and increasing injury risk.[54-56] Undetected proprioceptive deficits can predispose the dancer to injury, delay rehabilitation, or pose the risk of re-injury.[3,19] Results from testing proprioception in athletes with recurrent ankle sprains, for example, show them to have less ankle joint position sense than non-injured athletes,[57] and diminished perception of inversion and eversion movements as compared to controls.[58] Undetected proprioceptive deficits can lead to both peripheral and central alterations in function, such as joint laxity and instability, malalignment, localized weakness, diminished muscle reaction time, and altered body schema and central motor programming.[7,59,60] Poorly rehabilitated injuries may interfere, for example, with the strength of the reflex arc, leading to altered joint stability and motor control, as has been reported in cases of knee and ankle joint injury, post-surgery, and traumatic osteoarthritis.[3,7,19]

Further, because of its intimate relationship to balance, proprioception underscores our sense of safety and confidence in daily navigation. Thus, the psycho-physical impact of small proprioceptive deficits is important to consider after injury. Although surgical and rehabilitation outcomes may have been successfully met after lower extremity injury, if proprioception is insufficiently restored, or if the athlete feels insecure and unstable on the joint, full performance is compromised, and there is a higher risk of reinjury.[3,59] Severely impaired or absent proprioception negatively affects not only the quality of the individual's motor control, but also the way that individual perceives and interprets the behavior of others.[61] Deafferentation studies have shown that people who lose the ability to feel their bodies accurately through illness must rely largely on vision and cognition to carry out the simplest movements.[62]

Proprioceptive training is believed to be beneficial in preventing lower extremity injuries, as well as reducing recovery time and adding protection against re-injury.[7,59,63] Known benefits of proprioceptive training after knee and ankle injury in athletes include improved postural stability (balance),[56] flexibility,[64] joint position sense, stabilization, and faster muscle reaction time,[60] and ultimately a decreased incidence of re-injury. Whether proprioception itself actually improves with training is controversial.[13] Adaptations occurring during rehabilitation through perturbation training are thought to be mediated by changes in feedforward processes, affecting the speed of anticipatory reactions during fast movements, with concurrent proprioceptive feedback being less important.[3,13]

Proprioception should be an important part of the dancer's fitness profile.[65] It should be routinely screened in dance, with deficits recorded, proprioceptive training initiated, and progress tracked; especially, the screening should be repeated periodically if there is a history of injury. Traditional screenings for deficits in proprioception include tests in which subjects detect the threshold of passive joint movement. For static joint position sense and joint movement, the examiner passively moves a digit or limb while the subject, with eyes closed, mimics with the opposite limb or verbally describes the movement direction. Problems with this type of screen include sensitivity; the dance population may be too functionally advanced for this simple measure to detect differences.[66] Second, although relatively easy to execute, these tests are difficult to interpret if there are subtle deficits that may emerge under more active conditions of motor execution with and without injury.[3] For example, the timing and amplitude with which the peroneal muscles fire under static conditions does not reflect their responsiveness during at-risk conditions for injury (e.g., the landing phase of walking, running, or jumping).[13] Finally, these screens are inadequate as training tools or as outcome measures to track progress.[59]

Reliable and valid testing for proprioceptive deficits should include comprehensive balance testing.[3,59] Depending on the equipment used, balance tests can assess postural sway and limits of stability, sensory organization, foot contact pressures, and muscle activation patterns. Balance batteries attempt to model real perturbations, such as near or full falling, under altered sensory and environmental conditions (e.g., with eyes closed or on an altered surface), as well as examining joint loading at various phases (e.g., landing from a jump). Balance drills done on various surfaces with eyes open and closed help assess the relative contribution to balance of various neural afferents (visual versus vestibular or proprioceptive) and, by inference, joint stability.[59] Tests that are simple to administer and require little equipment include the clinical test of sensory organization and balance, or "Foam and Dome,"[5] in which six different test conditions discriminate somatosensory from visual and vestibular deficits.[5] Other simple clinical tests include rocker (wobble) board protocols or the Five-Star Balance Test.[67] Platform posturography, such as the NeuroCom® or Balance Master® system, uses a moving force platform and visual surround to quantify limits of stability and discrimination of sensory organization.[59] Dance-specific balance batteries need to be developed and validated that also test dancers in traditional foot positions (parallel, first, second, demi-pointe, and pointe).

Rehabilitation

Once assessed, comprehensive rehabilitation of lower extremity injuries includes balance training and proprioceptive exercises along with strengthening, flexibility exercises, and sport- or dance-specific movements.[19] Rehabilitation of proprioception includes a spectrum of interventions that use: 1. modalities, manual therapy, and other receptive body therapies and passive maneuvers; 2. bracing and taping; and 3. perturbation training, a progression of static and dynamic exercises to destabilize the injured joint or whole body balance. These exercises include: 1. augmenting joint position sense and muscular co-activation for dynamic joint stabilization (e.g., static uni-legged standing for ankle injuries); 2. activating postural synergies for reactive neuromuscular control; 3. increasing the speed, force, and duration of muscle activation around injured joints in non-weightbearing and weightbearing; and 4. challenging balance in dance-specific activities.[19]

Although protocols reported in the literature vary in terms of exercise modes, intensity, frequency and duration, perturbation exercises in altered sensory conditions challenge the body's normal responses to anticipated environmental stimuli.[8-10] Graded, potentially destabilizing forces (manual, surface perturbations) are applied to the injured joint during dynamic activities that challenge sensory organization of balance.[9] Retraining proprioception post-injury theoretically addresses multiple levels of central nervous system mediation in motor control: reflex spinal level, brainstem level (equilibrium and righting responses), and cortical level.[3,19] Exploiting reflex levels of receptor sensitivity alone is insufficient for full motor control, as receptors perform differently under active, goal-directed (as opposed to passive) conditions.[68] Exploiting reflex stimulation to gain flexibility, as in PNF contract-relax stretching or through self-employed manual therapeutic procedures (e.g., pressing on a tendon to relax a muscle), does not appear to have lasting value for motor re-programming.[68]

Comprehensive approaches to balance training can include a combination of wobble board protocols, Pilates reformer training, therapeutic ball and disk exercises, plyometric training, or mini-trampoline exercises. Employing sudden alterations in direction and speed of movement, along with impulsive loading, as in hopping, jumping, and plyometrics, helps to achieve these goals. By adding eyes-closed conditions, variable surfaces and multitasking, sensing, perceiving, and interpreting sensory input is challenged. Single leg stance with eyes open and eyes closed for specified durations can progress to unilateral and bilateral stance on foam, weight shifting, stepping, marching, walking, hopping, leaping, and jumping, all with additional interferences such as talking or counting backwards by 3's, catching a ball, or holding a glass of water.[69] Repetition and reinforcement of goal-directed, dance-specific training with real space-time values helps consolidate higher level learning, memory, and recall.[19] Protocols also should help dancers exploit multiple joint combinations in closed- and open-chain positions to develop flexible and novel strategies for movement.[3,48]

Further Considerations for Research

In addition to what dancers can learn about proprioception from rehabilitation and conditioning protocols, other aspects of dance training also impact proprioceptive responsiveness. The use of mirrors in the dance studio, for example, has been the recent focus of a number of studies.[70-72] Critique of their use centers mainly around the conflict of visual versus kinesthetic information as a source of motor learning. Small sample sizes and other methodological considerations, as well as contradictory results, beg a number of questions and require dancers to regard the conclusions with caution. Nonetheless, consensus appears to support the notion that mirrors are important in confirming the accuracy of movement in the later stages of motor learning, but should be avoided as the *sole* source of feedback in earlier stages of learning. Investigation as to the effect of mirrors on age and stage of learning of the dancer, type and degree of difficulty of the material being presented, and whether cueing is implicit (focusing on internal proprioceptive cues to control movement) or explicit (focusing on the goal of the movement) are just some of the possibilities for future research.[73]

In summary, proprioception appears essential to dancers, both to prevent injury and to enhance technique and performance. Dance educators and dance medicine specialists can share their knowledge to adapt exercises to suit the evolving requirements of dancers' fitness. Validation of dance-specific guidelines for proprioceptive training protocols still are needed,[74] as well as the integration of exercises to challenge proprioceptive "acuity" in the dance studio.

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