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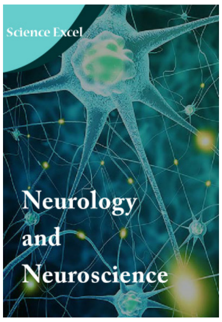

A Concussion-Avoidance Training to Generate Neck Stiffness as a Conditioned Reflex

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Abstract

Impact-induced rotational accelerations of the head are critical to the severity of the consequences of concussions. Here we describe a concussion-avoidance training (CAT) to increase neck stiffness and thereby reducing impact-induced head rotations. The goal of the CAT is the learning or acquisition of dynamic neck stiffness as a conditioned reflex or response (CR) to appropriate conditioned stimuli (CS) for the reduction of concussion risk. We first discuss the neuroscience of conditioned responses in classical conditioning as it applies to motor learning and athletic training. We then describe the practical implementation of the CAT, including the delivery of CS, the validation of CR, and other relevant information. Lastly, we made an effort to estimate quantitatively how significant can one expect the CAT to reduce concussion risk by considering the biomechanics of the head-and-neck.

Introduction

Concussions or mild traumatic brain injuries (mTBI) are consequences of inopportune interactions between an impact force and the head, causing the head (and brain) to move rapidly. Repetitive mTBI can lead to chronic traumatic encephalopathy (CTE), which is a degenerative brain disorder that currently has no cure [1,2]. Treatment and clinical management of the symptoms of concussions and CTE are costly, both in human and in financial terms. Prevention of concussion is therefore important. At present, there is no proven effective prevention for mTBI.

When the human head is hit by an impact force, impact-induced movement of the head is governed by Newton's second law of motion, $f = m_h a_h$, where [m_h] is the mass or inertia of the head and [a_h] is the head acceleration as a result of the impact. Since the severity of the brain injury is largely determined by the magnitude of impact-induced head acceleration [a_h], we now rewrite this equation as $a_h = f / m_h$. Thus, one can reduce the risk of brain injury or concussions by having a larger [m_h], thereby decreasing [a_h].

Neck strength is the capacity of the neck to exert force while neck stiffness is the ability of the neck to resist force. As early as 2007, it was recognized that a stronger and stiffer neck could increase the effective mass of the head, [m_h], and thereby reduce impact-induced head acceleration [a_h] [3]. In the ensuing years, numerous experiments were designed to test the effect of neck strength on concussion risk, albeit with mixed results. Isometric strength did not help reduce concussion risk [4]. Increased cervical muscle force did not influence short-term (<50 msec) head kinematics [5]. Multiple systematic reviews have concluded that neck strengthening interventions did not reduce impact injury risk [6,7]. These efforts have helped cast a negative shadow on the role of neck strength in mitigating concussion risks [8]. In the meantime, neck stiffness remains relatively unexplored, possibly because neck stiffness is technically more difficult to measure [9]. However, close to neck stiffness, anticipatory neck muscle activation was found to reduce impact-induced head accelerations [4,10,11].

A stiff neck immobilizes the head-and-neck and is incompatible with athletic performance. In sport medicine, therefore, the type of stiffness that can help reduce concussion risk must be dynamic, preferably occurring transiently just prior to the moment of head impact. Available data suggest that dynamic neck stiffness (DNS) or anticipatory co-activation of the synergistic as well as antagonistic neck muscles can lead to a reduction in impact-induced head acceleration [4,10-12].

Our working hypothesis is that neuromuscular control of head-and-neck plays an important role in DNS and can contribute to concussion risk reduction or prevention. Moreover, motor learning via the process of *classical conditioning* can influence

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the neuromuscular control of head-and-neck and produce the desired dynamic increase in neck stiffness during or prior to a head impact. This is the one single feature that makes concussion-avoidance training (CAT) based on classical conditioning and dynamic neck stiffness different from static neck-strength training [4-7]. A critical question is whether a training protocol consistent with the practice of classical conditioning can realistically and effectively produce a conditioned response (CR) with the requisite timing and the magnitude of DNS to reduce concussion risk in a significant manner. In this report, we argue from neuroscience principles that such a training protocol is highly feasible. We also argue from head-and-neck biomechanics that our CAT can be expected to significantly reduce concussion risk.

The Neuroscience of Conditioned Reflexes

A good example of motor learning to enhance DNS is classical conditioning of the eyelid response or eyeblink conditioning. Classical conditioning causes specific and *de novo* modifications of synaptic circuits built from existing brain cells [13-16]. Interestingly, this process does not involve the generation of new brain cells, a process that does not occur to a significant extent in the adult human brain. Rather, the neuroscience basis of the learned behavioral or neuroplasticity in classical conditioning involves structural and functional modifications at the synaptic level. We choose eyelid response conditioning as our example because this has been studied in detail as a prototype of classical conditioning [13-16].

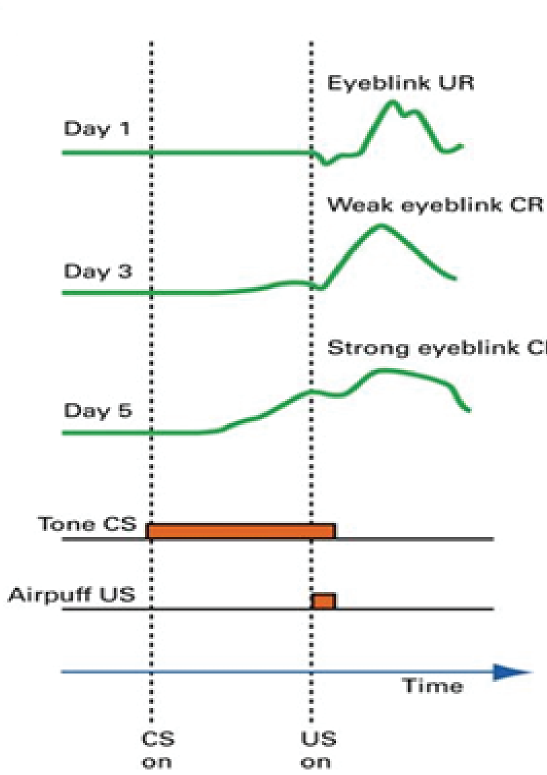

Figure 1. The emergence of CR in classical eyelid response conditioning – the magnitude, timing of CS and US, and the time course of CR [33]. Copyright © 2010 Worth Publishers. Used with permission.

In eyeblink conditioning, the key training parameters are the conditioned stimulus, or CS, and the unconditioned stimulus, or US. Typically, the US gets the attention of the subject in training because the US is mildly noxious, surprising, or unpleasant, such as an air-puff to the eye. In untrained subjects, a US always and unconditionally elicits a UR (unconditioned response). In the case of the air-puff as the US, the UR is a defensive eyelid response that protects the eye from the air-puff (Fig.1, Day 1, Day 3, and Day 5 traces). By contrast, the CS is typically a neutral sensory stimulus, such as a brief tone, that will never elicit any response resembling the UR in untrained subjects. Protocols in classical training typically entails a repetitive pairing of CS and US in successive training trials. A conditioned response (CR) gradually and eventually emerges during training as the subject in training gradually makes or learns an association between the CS and US. In eyeblink conditioning, the CR is the eyelid movement in response to the CS, such as a tone, that *precedes in anticipation of* the US, such as an air-puff to the eye.

The naïve, or the untrained, individual will not execute the eyelid response to the tone because the naïve brain, or the brain before training, does not have the requisite brain circuitry to generate the eyelid response to the CS. Without the requisite brain circuity, there can be no CR (Figure 1, Day 1, at the beginning of the conditioning). By pairing the CS and the US repetitively, the brain learns in time to make the association of the CS and US and creates an appropriate CR in response to the CS (Figure 1, Day 5 trace). During this learning period, the necessary brain circuitry is being constructed so the brain can respond to the CS with the appropriate CR. Once the brain circuitry is fully in place, a mere presence of the CS will reliably lead to the generation of the appropriate CR without the presence of US. Training is the process that helps building or remodeling the synaptic connections, so the tone becomes capable of activating cells controlling the eyelid movement. Successful acquisition of the CR simply signifies the operational presence of that modified brain circuit. Learning to create all kinds of CR to a variety of otherwise neutral stimuli is at the heart of human motor learning.

The list of the most likely brain structures for eyelid response conditioning includes the cerebellum and its related brainstem structures [13,14]. The cerebellum plays a critical role in first recognizing and later searching for conditioning cues as well as in orchestrating the activation and inactivation of the appropriate set of muscles involved in the CR. The cerebellum is therefore instrumental in motor learning. An important feature of cerebellar motor learning is that the performance metrics such as the magnitude and the timing of the motor response will improve with repetition or training. A second important feature is that the appropriate CR is generated effortlessly at a subconscious level, without the subject having to think about it consciously. It is in this way that we envision the CAT will lead to the DNS as a desirable CR.

At present, motor learning by conditioning is broadly categorized as classical conditioning or operant conditioning [17,18]. So far, we have treated the CAT as a task in classical conditioning. More scientific and technological R&D will be needed to improve and facilitate the CAT as a motor learning task by involving brain mechanisms of classical as well as operant conditioning. Ultimately, a long-term objective is the rendering of the most efficient acquisition of the most desirable motor response for the most effective reduction of concussion risk.

The Characteristics of Conditioned Responses

One can train a human subject or a laboratory animal such as a rabbit or a mouse to acquire anticipatory eyelid movement in response to a tone or other cues without instructing or otherwise communicating to the subjects being trained what are required of them or how to accomplish the learning. That is, in classical conditioning, the subjects will learn to execute the appropriate CR without any explicit instructions. In addition, both the learning or the acquisition of the CR in naïve subjects and the execution of the eyelid response in trained subjects operate at the subconscious level. An engineer must program into a robot the detailed movement strategy, including the trajectory, the force, the distance, and the weight of the ball, etc., so the robot can make a free throw. A basketball player learns to shoot a free throw without being consciously aware of the detailed biomechanics of shooting a free throw.

In the CAT, the desired CR is the DNS that will reduce concussion risk. One way to express the CR is the co-contraction of head-and-neck muscles [12]. This means the simultaneous activation of synergistic as well as antagonistic head-and-neck muscles. By design, synergist muscles and antagonistic muscles are typically located on the opposite sides of a joint and are normally activated "out of phase" in order to create movements about a joint. Co-contractions of synergistic and antagonistic muscles immobilize the joint and therefore are not a part of the normal, pre-programmed neuromuscular activation pattern by the nervous system. Such immobilization, however, is exactly what we need to reduce concussion risk. It is therefore important that the athletes acquire a special motor programming and learn to execute this type of movement. Stronger head-and-neck musculature will, of course, provide a better foundation for more robust DNS. By itself, neck strength may be a necessary but not a sufficient contributor for concussion risk reduction [6,7].

The timing relationship between CS and US is also critical [19]. For example, in the paring of CS and US in eyeblink conditioning, if the tone (CS) always precedes the air puff (US) precisely by 250 msec, then the eyelid movement (i.e., nictitating membrane) or CR will always be at 250 msec after the tone. If during the training, the tone (CS) always precedes the air puff (US) by 400 msec, then the eyelid will always move (CR) at 400 msec after the tone. The timing relationship between the CS and the CR in classical conditioning is a critical asset of the CAT and contribute handsomely to the effectiveness of the CR in mitigating concussion risk. In American football, consider a player is carrying the ball while an opposing player is rushing head-on to attempt a tackle. Assume the speed of the first player relative to the second player is 10 meters per second; at two meters away, physical contact will occur in 200 msec. A latency of 200 msec between CS and CR is therefore consistent with a CS of an opposing player appearing within a personal safety space of two meters. This latency is well within the operating range of a CS and a CR in classical conditioning.

Once acquired, the conditioned response can be rather consistent or secure until its extinction, also a form of conditioning. Extinction often involves presenting the tone, repetitively, without consistently pairing it with the air puff to the eye. Indeed, extinction, or the unlearning of an established CR, is also motor learning or classical conditioning in which the brain learns to dissociate the ex-CS with an established CR. In the case of most athletes, extinction of the DNS as a CR should be quite unlikely.

Implementation of the Neck-Stiffness Conditioned Response

Defining CS

The CS in our CAT consists of the most likely events immediately leading to a potentially injurious head-impact event. Defining CS is an exercise in evidence-based search. For example, studies on football have shown that, impacts to the head can come from the body of another player (45%), the head of another player (36%), or the ground (19%); concussions can occur during tackling (tackling 41%, tackled 22%), blocking (blocking 19%, blocked 11%), diving or leaping (5%), and others (2%) [20]. Taking advantage of such information, one can design the CS as a mixture of short videos (under one second in duration) covering all the scenarios mentioned above with the correct weighing factors. Current technology in virtual reality devices can facilitate greatly the delivery of the CS. There are similar evidence-based data for major causes of injuries in other sports, such as soccer [21]. In this way, it is feasible for the software developer to design CS in a manner that is custom-tailored specifically for concussion avoidance in each sport and in a data-driven manner.

Defining US

The US should be ideally a stimulus that can consistently and reflexively cause the maximal co-contraction of all the head-and-neck muscles to "freeze" the neck. The most effective US for concussion-avoidance training is likely to be a somatosensory stimulus, such as a mild electric shock to a sensitive part of the head-and-neck. If such electric shock is not acceptable, one can take advantage of the startle reflex by using an auditory stimulus such as a harsh yell from a much-feared coach. From a neuroscience perspective, an effective US must also be one that can elicit a strong response in the inferior olive in the brainstem. The inferior olive is known to be sensitive to sensory stimuli that are non-routine, surprising, out of the ordinary, and mildly noxious or unpleasant [14,22]. We have shown in our laboratory that a visual cue delivered (in virtual reality goggles) as a huge cartoon hand coming at the forehead of the individual to act as an exaggerated glabellar tap can effectively elicit robust motor activations even beyond the co-contraction of synergistic and antagonist muscles in the head-and-neck [12,23].

Additional Practical Considerations

How long and how much training effort will be required for the acquisition of a dynamic increase of neck stiffness to reduce concussion risk? Extensive literature exists on classical conditioning of the eyelid response or eyeblink conditioning, including the most effective training paradigm (e.g., the number of repeated trials in each training session as well as how many training sessions, etc.) [14]. In nictitating membrane conditioning, rabbits can reliably express the CR in ~5 days with daily sessions of 70-100 CS-US pairings [24]. By contrast, young human subjects reach a similar level of CR expression in ~40 CS-US pairings in one day [25]. It is to be expected that the time course for the acquisition of a robust DNS may be quite similar. This is because the number of muscles involved in eyeblink conditioning is few (*orbicularis oculi* and *levator palpebrae superioris muscle*), and the number of muscles involved in neck stiffness is also few (*m.sternocleidomastoidus* and *m.trapezius*). However, the detailed and exact time course may vary with the individual, the training frequency, the CS used in the training, and whether the trainee had been exposed to other forms of motor learning.

In sum, the generation of the CR via an appropriate CAT is all but assured by the known capability of the human nervous and motor systems. Modern technology such as virtual reality goggles can offer many options for the delivery of the CS and US.

The Expected Extent of Impact-force Dissipation

The physics of a head-impact event is governed by Newton's Second Law of Motion [$f = m_h a_h$]. Impact-induced head acceleration [a_h] is inversely proportional to the effective mass of the head [m_h]. To examine the efficacy of the reactive countermeasure, it is therefore critical to ask the question: How will the countermeasure increase the effective head mass?

To answer this question, we examine a headbutt event [26]. In this incident, a goat gave a cow a concussion. The cow clearly had a more massive and stronger head-and-neck. However, because the goat was able to walk away and the cow was not, impact-induced head acceleration [a_h] of the goat must have been smaller than that of the cow. The goat must have had superior DNS which increased its [m_h]. The data from meat suppliers indicates that goat's and cow's head weigh in at 4-6 pounds and 35-40 pounds, respectively [27,28]. By these figures, the DNS in the goat must have increased its effective head mass [m_h] by the mean of [35-40] / the mean of [4-6] or a factor of 7-8.

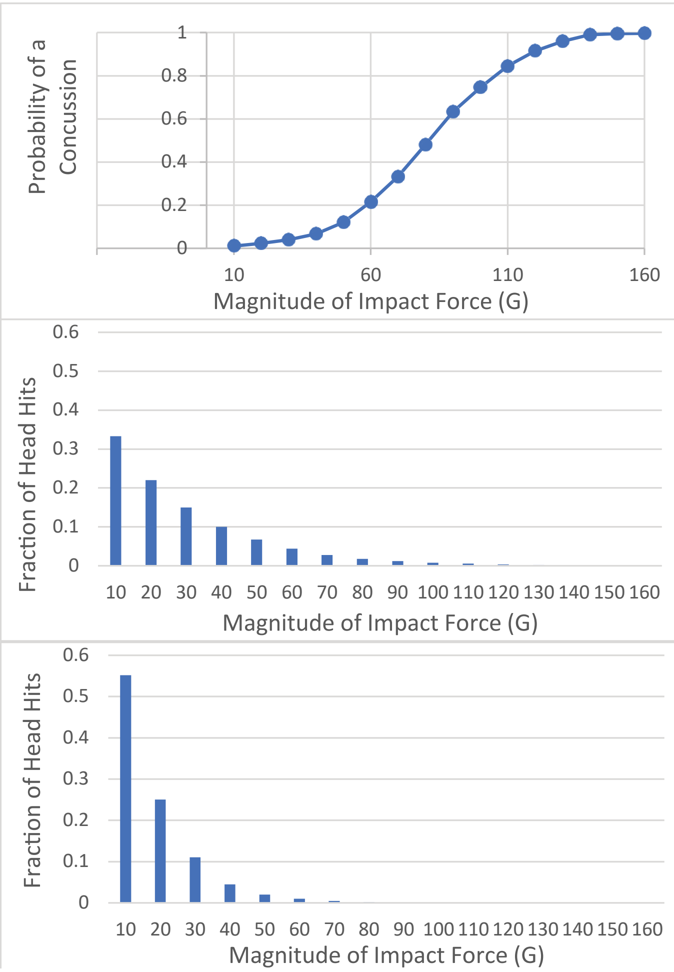

Figure 2. *DNS reduces TBI risk by increasing [m_h] and decreasing [a_h].*

In the upper panel of Figure 2, we plot the probability of concussions as a function of the magnitude of the impact force. This data is taken from Greenwald et al. [29]. The middle panel is a histogram showing the fraction of head hits as a function of impact force from football players measured by sensors [30]. In this histogram, the sum of all the bars is unity while the values of individual bars follow a Poisson distribution. Multiplying Y values of the two panels across accelerations bar-for-bar and adding the products will yield 0.085, essentially a relative measure of the average risk of concussions for a football player [31,32]. If we can reduce impact-induced head accelerations by a factor of 2, we compress the bars to the left (lower panel). Instead of 8.5%, the relative risk measure becomes 2.8%, a 67% reduction of concussion risk. A factor of 3 will lead to an 80% reduction of concussion risk. Approaching 80% concussion protection, therefore, is a promising goal and perhaps within reach in children and women if we can expect a neck musculature ~25-30% of the goat. Individuals may be able to do better if they are endowed with great neck stiffness due to larger neck strength and girth.

Epilogue

Childhood is a golden age to learn all things. There is a critical window during childhood when the ability to learn sports and other things is the greatest. Learning sports at a young age is often credited as a major factor in highly accomplished athletes as adults (the tennis player Maria Sharapova and the golfer Tiger Woods, to name just a few). We believe that player safety is an integral part of athletic skills and therefore should be learned at an early age when the brain is the most plastic.

Throughout human history, we are often better off when we meet the challenge head-on without retreating to a protective bubble. Experts have begun to rethink the approach to deal with a wide range of human conditions, including food allergies. Introducing a small amount of peanut gradually while monitoring the child carefully can allow the immune system to learn so that the child can overcome the peanut allergy, an outcome that is considerably better than avoiding peanuts for life. We should not want our children to avoid learning teamwork, competitiveness, and grit for fear of concussions.

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