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A Review on Ocular Biomechanic Models for Assessing Visual Fatigue in Virtual Reality

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ABSTRACT With the wide spread of affordable virtual reality headsets, virtual environments are rapidly changing the way humans interact with reality. Understanding the effects of virtual environments on the mental and cognitive state is essential. In addition, defining methods for measuring and assessing visual fatigue in virtual environments is still needed. While eye movements are tightly coupled to the mental state, analysis of eye movement can add insights for safer virtual environments. Biomechanical analysis has been used extensively in the analysis of human movement. Simulation of different scenarios such as injuries and surgeries provided insights and solutions to problems that were otherwise impossible. This includes understanding the effects of changing insertion points of muscle on range of motion or how muscle activation can affect the motion produced. Extending the use of biomechanical simulation analysis into eye movement can be used to deepen our understanding of how virtual environments affect our visual and mental capabilities. This paper presents a thorough review on ocular biomechanics and ocular models in literature. We start with a brief introduction on the anatomy of the eye and eye kinematics. In addition, properties of the extraocular muscles (EOM) are described and the difference between EOMs and skeletal muscle is highlighted. The challenges facing biomechanical simulation and analysis of eye movement are presented along with the role of ocular models in assessing visual fatigue. Furthermore, the compatibility of available biomechanical tools to analyze ocular movements is discussed.

INDEX TERMS Biomechanics, ocular, virtual environments, extraocular muscles, visual fatigue, ocular motility, OpenSim.

I. INTRODUCTION

Affordable virtual reality (VR) headsets have changed the way we interact with the environment around us. With their rapid development, applications for virtual environments (VEs) will spread to all aspects of life. Initially, VEs needed expensive setup, and thus they were only used in military training and in flight simulators. However, nowadays, inexpensive headsets use smart phones to give users a virtual experience such as Google Daydream and Samsung Gear. This made it easier to integrate VEs in education [1]–[4], psychology [5], [6], in addition to military [7], law-enforcement [8], even rehabilitation [9], [10] and evaluation of social skills for children [11]. This makes assessing the effect of VEs essential for a safer experience.

The extensive use of VEs in our lives raised rapid concerns regarding their effects on cognitive load and the human visual system (HVS) [12]. Poorly calibrated optics and hardware in HMDs can cause poor binocular synchronisation between left and right eyes. This, in return, is perceived as headache and nauseating uncomfortable experience. Recent hardware advancements solved these problems by redesigning the head mounted display (HMD) and helmet mounted display (HeMD) systems with more HVS-compatible optics modules. HMDs are now equipped with Inertial Measurement Units (IMU) for high speed head tracking. They also have stereoscopic micro-displays with optical lenses that have higher resolution and larger field of view [13]–[17] and some VR headsets now come with embedded eye-trackers [18]. These advancements lead to ground breaking products such as Microsoft HoloLens, HTC Vive and Oculus Rift. However, subjective experimental trials show that visual discomfort is still apparent in the extended usage of HMDs and HeMDs [12]. This creates a need to define objective methods that can assess visual fatigue. Real-line fatigue detection can provide a useful tool for VE designers to create more fatigue-resistant environments.

Visual fatigue in VE is caused mainly by the vergence-accommodation conflict (VAC) [12], [15] or mismatch between perceived and virtual depth. Another cause of fatigue is motion, especially vibrational motion experienced while using helmet mounted displays (HeMDs) [19] while driving on rough terrains, as in military training. Motion sickness can be experienced in virtual environments whether due to visually moving backgrounds without physical movement (cybersickness) or due to simulated motion (simulator sickness) or bending the head out of the axis of the rotation of the visual background (optokinetic motion sickness) [20]–[23].

Studying eye movement has been a tool to gain insights into human behaviour, muscular and mental disorders and dementia [24]–[28] and has been related to visual fatigue [29]–[43]. Therefore, investigation of eye movement in virtual environments and the quantification of fatigue through eye movement is an interesting method for a safer immersive experience. It can be used as a tool for visual ergonomics, especially through the use of biomechanical analysis.

Biomechanical analysis and simulation has been used in ergonomic evaluation of various activities, which can be extended into visual tasks. Open source platform OpenSim [44], developed and supported by The National Center for Simulation in Rehabilitation Research (NCSRR), provides biomechanical tools and models for different movement systems [45]–[50].

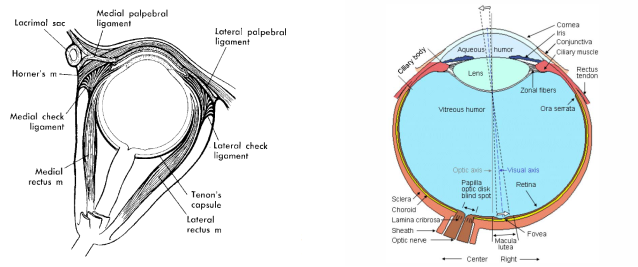
In this paper we will review the development and progress of biomechanical ocular models and the challenges to integrate them into full human body biomechanical models to perform analysis and simulation of different eye movement systems for visual ergonomics applications. We will also discuss the benefits and challenges of using ocular biomechanics to measure visual fatigue. The paper is organised as follows. Section II describes the anatomy and the kinematics of the human eye. The characteristics of the extraocular muscles (EOMs) are presented in Section III with a highlight on the difference between EOMs and skeletal muscles. Section IV describes visual fatigue and the methods used for assessing it, with a highlight on visual fatigue caused during immersion in virtual environments. The benefits and challenges of using ocular biomechanics in assessing of visual fatigue are discussed in Section V and Section VI. A conclusion and summary of the paper is presented in VII.

II. KINEMATICS OF EYE MOVEMENT

The kinematics of the eye movement focus on the different rotations an eye can perform. The left and right eye move in coordination with each other. Each eye presents a slightly different image of the environment to the brain. As long as the difference between the two images, known as binocular disparity is not too large the brain can interpret depth and fuse the two images into a sharp single image. For that to happen, the eyes move in one of two modes with respect to each other. Either in the conjugate mode, where both eyes move in the same direction, or in opposite directions as in the disjunctive mode (converging or diverging) [28], [49], [51]. A brief introduction the the anatomy of the human eye and the different eye movement systems will be described next.

A. ANATOMY OF THE HUMAN EYE

The human eyes are nested in two bony cavities called orbits [52]. Using six extraocular muscles, the eyes perform different rotational movements. In addition, connective tissues, smooth muscles, nerves, blood vessels and other visual structures are enclosed in the orbit surrounding the eye as shown in Fig. 1.



(a) (b)

FIGURE 1. **Anatomy of the human eye. (a) Superior view of the human eye inside the orbit cavity, only the medial rectus and lateral rectus muscles shown. The Tenon's capsule that enclosed the eye-globe and the ligaments of some of the muscles are shown [53]. (b) Superior view of a horizontal section of the right human eye. The visual axis passes through the fovea which is positioned in the center of the macula lutea of the retina [54].**

Investigations of the anthropometry of the human eye found that the radius of the eye-globe is, approximately, 24 mm. Post-mortem human eyes were studied [55], with donors ranging in age from 1 day to 104 years, the study showed no significant difference between globe horizontal and vertical diameter as assumed earlier. The average vertical and horizontal diameters for all eyes over two years of age were 24.26 ± 0.96 and 24.16 ± 0.97 mm, respectively. The interpupillary distance, that is the distance between the centers of the pupils, range from 53 to 78 mm [56]. Figure 1(b) is a closer look into the eye-globe showing the different constituents of the eye. The constituent responsible for sharp central vision (foveal vision) is the retinal fovea. It is a small central pit in the center of the macula lutea of the retina. The visual axis passes through the center of the fovea and the centre of the pupil.

For a clear acute vision, the image of the object must be held steadily on the central, foveal region of the retina. This imposes a two-fold limitation problem; the steadiness of the object and the distance from the fovea. Visual acuity deteriorates if retinal image move more than 5 deg/s especially for objects with high spatial frequency. It also declines if the image falls away from the retina, it can decrease by 50% if the image moves only 5 deg away from the foveal centre. For a clear, sharp vision, the image has to lie within 0.5 deg of the foveal center. This is why eye movements have one of two objectives, either to stabilise the image on the retina even with head movement, or to shift the gaze to a new point of interest. It is also important to note that eye movements, are coupled to head movements since the orientation of the eye-globe is limited by the orientation of the head. The movement of the head has to be compensated with eye movement or else the image will slip off the retinal foveal [28], [51].

B. EYE MOVEMENT SYSTEMS

Eye movement systems can be categorised into two categories; movements that hold the image of an object steady on the retina and movements that change gaze direction to bring image of an object onto the fovea. Fixation, vestibulo-ocular reflex and optokinetic reflex fall in the first category, while saccade, smooth pursuit and vergence are in the second category [28], [51], [57].

1) FIXATION

Fixation holds the image of an immobile object on the fovea while the head is steady. If the image of the object is perfectly stabilised on the retina, vision fades due to habituation, which is a decrease in response to a stimulus after repeated presentations. Thus, fixation has motions that are less than 1 deg and may include drift (slow random motion away from fixation point at very low velocity) and micro-saccades (small rapid motion to redirect eye to fixation point) [28], [57].

2) VESTIBULO-OCULAR REFLEX (VOR)

During brief head movement, eye movement is induced by the vestibular system to stabilise gaze and thus, ensure visual acuity especially during locomotion. The eye movement must compensate head movement by rotating at the same speed in the opposite direction. Angular (rotational) VOR stabilises retinal image during head rotation and depends on the semi-circular canals in the inner ear. Linear (translational) VOR, originated from the otolithic organs of the inner ear, induce eye rotation to compensate for translational movement of the head while fixating at a point [28], [58], [59].

3) OPTOKINETIC REFLEX

Optokinetic reflex stabilises the retinal image during a sustained head rotation. It is, also, induced by a large visual mobile scene, causing an illusion of self-motion. This reflex is very common when observing a scenery or poles on the side of the road, out of a moving car or train. With sustained head rotation, the vestibular response fades due to mechanical properties of the semicircular canals. VOR responds to high frequency head movement while optokinetic reflex complements the VOR and responds to sustained low-frequency head rotation [28], [51].

4) SMOOTH PURSUIT

Smooth pursuit is slow tracking of a moving target in the range of 1 to 70 $\deg/s$. Its purpose is to hold the image of a small, moving object on the fovea. It is similar to optokinetic as the eye moves due to a moving object, but smooth pursuit is a voluntary eye movement to track a small moving target and cannot be induced voluntarily without a target, while optokinetic is a reflex induced by large moving visual scenes. Smooth pursuit predominates over VOR and Optokinectic reflex. It cancels VOR in case of eye-head tracking, where the target moves in the direction of head movement. It also cancels optokinetic reflex when tracking a small moving target against the large background [28], [51], [57].

5) SACCADE

A saccade is a rapid conjugate eye movements that changes fixation from one point to another of both eyes simultaneously, usually occurs in scanning scenes or reading. It can also be an involuntary consequence (reflex). It is characterised by very high initial acceleration (up to $40,000\ \deg/s^2$) and peak velocity (up to $600\ \deg/s$). Saccades may span from 30 to 120 msec. Head motion is involved when target motion exceeds 30 deg. The main purpose of saccades is to bring the image of a new target onto the retinal fovea rapidly [28], [51].

6) VERGENCE

Vergence is a disjunctive movement of the two eyes in opposite directions to each other, to stabilize the image of near or far objects on both foveae. It reach maximum velocity of 10 deg/s over a range of 15 deg. This movement is stimulated by focusing error and binocular disparity. Eyes converge when moving from a far to a near target and diverge when the opposite happens, maintaining parallel lines of sight when target is at optical infinity [28], [51], [57], [60].

C. EYE TRANSLATIONAL AND ROTATIONAL MOVEMENT

Translational movement is negligible because of the stiffness of the Tenon's capsule which surrounds the eye-globe as shown in Fig. 1(a) [28]. The rotational movement occurs around one of three axes intersecting at the center of the eye-globe and perpendicular to one-another. The antero-posterior (x-axis), coincide with the gaze direction, the vertical (y-axis), and the horizontal, lateral-medial (z-axis). The vertical and the horizontal axes are assumed to lie in Listing's plane [28], [53], which is a plane fixed in the orbit passing through the center of rotation and the equator of the globe when the eye is in the primary position and perpendicular to the gaze direction (x-axis). Many attempts had been made to define the primary position. In [61]–[63], it was defined as the position from which any pure horizontal or pure vertical rotation is not associated with any torsion of the eye-globe. It is the position from which all other ocular movements are initiated. In [64], the primary position is defined as the position with erect head and eye looking at an object at infinity and lies at the intersection of the sagittal (antero-posterior) plane of the head and a horizontal plane passing through the centers of rotation of the two eyeballs. Another definition for the primary position is with reference to Listing Law [28]. It is the position where the line of sight is perpendicular to Listing's plane and from which any purely horizontal or purely vertical movement initiated, will not have any torsional component. Figure 2(b) shows the right eye

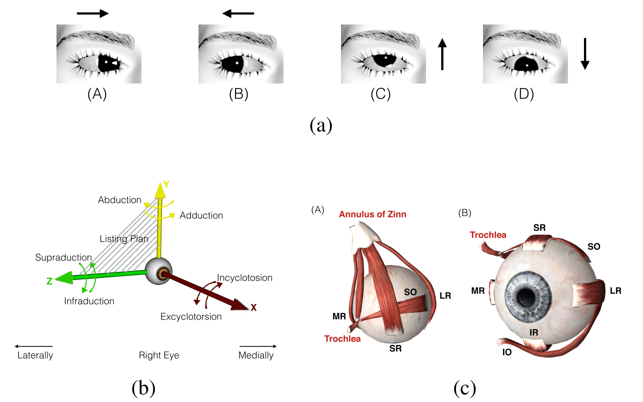


FIGURE 2. **Human eye movement terminology, rotation axes and extraocular muscles illustrated. Top: Secondary positions for right eye: (A) Adduction, (B) Abduction, (C) Supraduction and (D) Infraduction. Bottom-Left: Right eye showing the axes and the different rotation directions used. Listing plane is illustrated, it is the Y-Z plane. Bottom-Right: Left eye muscles shown from (A) Superior view, (B) Anterior view. The six muscles are shown along with the annulus of Zinn and the trochlea. The names and abbreviations of each muscle is shown in Table 1 along with their actions.**

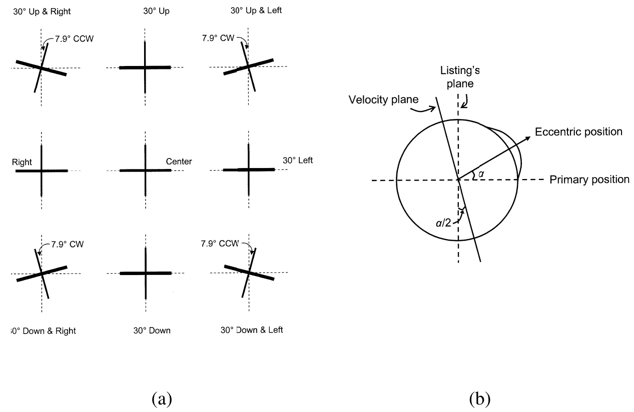


FIGURE 3. **Listing's Law. (a) Torsional positions of the eye as described by Listing's law, such that for each gaze direction, there is only one torsional angle. Nine eye positions are demonstrated. CW means clockwise from the subject's reference and CCW means counter-clockwise [69].**
(b) Listing's half-angle rule demonstrated, such that the velocity plane is rotated by half the angle of the gaze rotation. Listing's primary position and plane are shown [69].

with its rotational axis. Listing's plane is Y-Z plane, and thus x-axis is direction of the primary position. Listing's primary position does not coincide with central gaze which is looking ahead with no rotation in any direction. It is approximately $11-12$ deg temporal to central gaze [63], [65].

To avoid confusion, we will use the primary position to refer to central gaze, conforming with most literature and Listing's primary position to refer to the eye position with line of sight perpendicular to Listing's plane, when needed.

The rotations of one eye is called a duction movement. Adduction is rotation around vertical y-axis nasally, i.e. towards the nose, while abduction is the rotation temporally, i.e. towards the temple. Rotations around the horizontal z-axis upwards is called supraduction (elevation), while when rotated downwards it is infraduction (depression). Torsional rotation (can also be called cyclotorsions) around the line of fixation towards the nose is called incycloduction while torsion towards the temple is called excycloduction. A secondary position is a purely horizontal or vertical position. A tertiary position, also called oblique position, is a combination of horizontal and vertical rotations.

D. LISTING'S LAW

In theory, since the eye rotates in three-dimensions then it can take an infinite number of torsional positions at any eye orientation. However, Donder, in 1848, demonstrated using after-images [66] that this does not occur in reality. In his experiment, he looked at a red cross for a long period of time. After that, he looked at a blank screen in front of him. He found that the after-image cross stayed vertical when he looked up, down, right or left. However, the cross was inclined once he looked obliquely (e.g. up-right or down-left). Donder's law stated that for each gaze direction, there is only one torsional angle as illustrated in Fig. 3(a). Listing's law [67] quantified this torsional angle for each direction of gaze, by stating that the eye takes only gaze positions initiated from Listing's primary position by one rotation through an axis enclosed in Listing's plane. Listing's plane is orthogonal to the gaze direction with the eye in Listing's primary position [68].

To formulate a Listing's law equation, Robinson in [70] and [71] used Fick's coordinate system that defines axes moving with the eye, where θ, ϕ and ψ are horizontal, vertical and torsional angles of the eye positions, respectively. Positive rotation for each is in the abduction, supraduction and excycloduction directions, respectively. Thus, Listing's law was defined such that ψ is a single valued function of the θ and ϕ,

$$\psi = \sin^{-1}\left(\frac{\sin\theta\sin\phi}{1+\cos\theta\sin\phi}\right), \tag{1}$$

or using Helmholtz coordinates, where an eye position is described by a sequence of rotations starting from primary position. First, the eye undergoes a torsional rotation T around the gaze direction, then a horizontal rotation H and finally a vertical rotation V. So, from Wong *et al.* [68], [69], Listing's law can be expressed as,

$$T = -\frac{HV}{2}, \tag{2}$$

where T, H and V are all angles in radians. Positive values are clockwise, right and up, respectively. Figure 3(a) shows torsional angles at nine different positions [69].

The torsional angle of the eye varies with the horizontal and vertical positions. This expresses Listing's law with reference to the primary position. If the eye starts at an eccentric gaze, as shown in Fig. 3(b), the rotation axis lies in a plane that is inclined by half the angle of inclination of the gaze direction. This plane is called the velocity plane [68], [72]–[74]. Therefore, we can say that Listing's plane is a special case of velocity plane, orthogonal to the gaze direction [68], [69].

Another way to describe Listing's law is using quaternions and rotation vectors [75]. This can be done by defining eye orientation in terms of vectors aligned with the axes of rotation from the primary position, scaling these vectors to the angle of rotation, and defining torsion using head-fixed axis as rotation about the gaze direction in Listing's primary position [68], [76]. Using this coordinate system, Listing's law can be simplified as maintaining a zero torsion at all gaze directions [72], [74], [75], [77].

Experimental studies confirmed that the eye obeys Donder's and Listing's laws approximately at static tertiary gaze as well as under dynamic conditions [78], [79]. Saccades and smooth pursuit obey Listing's law. However, in horizontal and vertical vesticulo-ocular reflex (VOR), the rotation axis is inclined only by a quarter to a third angle as much as the gaze direction. During head roll, the axis is inclined as much as the gaze direction but in opposite direction to the head roll. However, translational vestibular response obeys Listing's law [28], [68], [80]–[82].

III. EXTRAOCULAR MUSCLES

Each eye-globe has six extraocular muscles (EOMs) controlling its movement as shown in Fig. 2(c). The four rectus muscles are lateral rectus (LR), medial rectus (MR), superior rectus (SR), inferior rectus (IR), and the two oblique muscles are superior oblique (SO), and inferior oblique (IO). The four rectus muscles originate at the annulus of Zinn. The annulus of Zinn encircles the optic nerve of the eye at its entrance at the apex of the orbit. The rectus muscles, as their names show, inserts medially, laterally, superiorly and inferiorly onto the globe. Insertion and origin points were determined by Volkmann [83] and modified by Helmholtz [61] through measurements in cadavers. These points were used by [45], [49], [65], [71], [84]–[86] in their ocular models.

TABLE 1. Actions of extraocular muscles. The table shows the action direction of each muscle in each of the three positions [53].

Muscle	Primary	Secondary	Tertiary
Lateral Rectus (LR)	Abduction	-	-
Medial Rectus (MR)	Addution	-	-
Superior Rectus (SR)	Supraduction	Incycloduction	Adduction
Inferior Rectus (IR)	Infraduction	Excycloduction	Adduction
Superior Oblique (SO)	Incycloduction	Infraduction	Abduction
Inferior Oblique (IO)	Excycloduction	Supraduction	Abduction

The role of each of the six extraocular muscles is summarized in Table 1 and the agonist-antagonist relationship between the extraocular muscles is summarised in Table 2. The primary action is the eye movement that is initiated from the primary position. The secondary action is related to secondary eye position were the eye is purely abducted, adducted, supraducted or infraducted as shown in Fig. 2(a). The tertiary action is related to oblique eye positions also called tertiary position where eye orientation has a horizontal (ab/adduction) and vertical (supra/infraducted) component.

TABLE 2. Agonist, synergist and antagonist relationships.

Position	Agonist	Synergist	Antagonist
Adduction	MR	SR and IR	LR, SO and IO
Abduction	LR	SO and IO	MR,SR and IR
Supraduction	SR	IO	IR and SO
Infraduction	IR	SO	SR and IO
Incycloduction	SO	SR	IR and IO
Excycloduction	IO	IR	SO and SR

Thus, MR and LR muscles are responsible for the horizontal adduction and abduction of the eye-globe, respectively. The SR and IR muscles primary vertical supraduction and infraduction of the eye-globe, respectively. And as a secondary action, they cause incycloduction and excycloduction of the eye-globe, respectively. Also, as tertiary action they, both, adduct the globe.

The action and anatomy of the oblique muscles were always a challenge [87], due to their mechanical complexity. The SO muscle originates from the annulus of Zinn. However, from a physiologic and kinematic standpoint [88], the trochlea acts as the origin of the muscle. That is because the muscle runs from the annulus of Zinn anteriorly parallel to the upper part of the medial wall of the orbit, reaching the trochlea. The trochlea is a tube 4 to 6 mm long formed mainly of cartilaginous or bony elements. After passing the trochlea, the SO muscle turns into laterally to its insertion on the eye-globe. SO has a primary action to incycloduct the globe. It also has a secondary action of depression and a tertiary action of abduction.

The IO muscle is the shortest of all the eye muscles. It originates near the lateral edge of the entrance into the nasolacrimal canal. The muscle runs from its origin backward, upward, and laterally, between the floor of the orbit and the IR muscle. It inserts by a short tendon laterally onto the globe. Unlike the other EOMs, the IO is almost wholly muscular, as it has the shortest tendon. IO has a primary action to excycloduct the globe. It also has a secondary action of supraduction and a tertiary action of abduction.

A. EXPERIMENTAL PROCEDURES TO INVESTIGATE EOMs

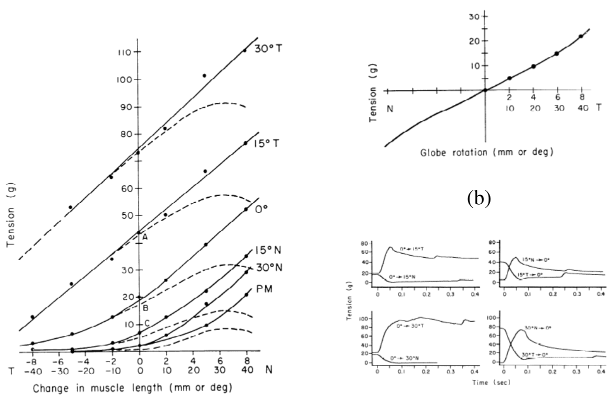
Attempts to understand the extraocular muscles and their role in different eye movement systems were performed during strabismus corrective surgery [89]–[94] at first then more non-invasive techniques [95] were used on normal patients during clinical experimental trials. MRI imaging has been used extensively to understand the inflection of muscle path with gaze change and location of pulley. It helped confirm the Active Pulley Hypothesis (APH) [96], [97].

In [89], Robinson *et al.* obtained length-tension relationship of human LR at different innervation levels by studying patients under topic anesthesia for a strabismus surgery. During the surgery, the MR and LR muscles, of the operated eye, were detached from the eye-globe and the LR was attached to a strain gauge to measure the isometric force. The vision of the operated eye was occluded and three procedures were performed.

In the first procedure, the strain gauge, connected to the muscle, cause it to changes length from its initial normal length at the primary position by ±2, ±5, and ±8 mm. At each length, the patient is asked to make saccadic fixation of 2 seconds with their normal eye to targets at angles ±50 deg and ±30 deg.

The second procedure is similar to the first procedure. It is used to measure length-passive tension relationship. The patient is asked to fixate the normal eye at a target that is positioned at an extreme gaze, out of field of action of the muscle under study. This is done to ensure that the muscle is completely relaxed. The length of the muscle of the operated eye is then changed using the strain gauge, as done previously.

The third procedure used the detachment of both horizontal recti muscles to measure the force needed to rotate the globe by steps up to 40 *deg*. The strain gauge is attached to the globe at the insertion point of the detached muscle and then it is used to abduct the eye and measure the produced tension needed. During all procedures, the head movement was kept minimum by use of vacuum sandbag pillow. The results of the three procedures can be shown in Fig. 4. Collins *et al*. [91], [92], [95] investigated the length-tension relationship of the horizontal rectus muscles (LR and MR) during fixation and saccadic eye movement using similar procedures. The length-tension curves were used to represent all EOM muscles by scaling them using relative strength (λ) of each muscle with respect to LR.



(a) (b) (c)

FIGURE 4. Resultant curves from clinical experiments during corrective surgeries [89]. (a) The curves show the length-tension for a partially innervated human extraocular lateral rectus muscle. The x-axis label shows the change of muscle length from the primary position length (mm) and the equivalent value in eye rotation (deg). Curve PM is the passive muscle tension. Solid lines represent the total tension while dashed lines are the active tension. (b) Steady-state relationship between tension applied to the human eyeball and its subsequent horizontal rotation illustrated. Both horizontal rectus muscles were detached in this procedure. (c) Time course of isometric tension of a human LR muscle during saccadic eye movement of 15 deg and 30 deg of the un-operated eye directed temporally (T) or nasally (N) and back again to the primary position (0 deg) with muscle held at its primary position length. High tension is developed when moving temporally since LR is responsible for this rotation (agonist) while it drops when moving nasally (antagonist).

For the eye-globe to rotate, the moment of force is needed to overcome the resistive tension of orbital suspension tissues. The steady state tension required to rotate the globe inside the orbital suspension tissues described in the third procedure above is shown in Fig. 4(b) [89]. The slope of the curve at the origin was reported as 0.5 gm/deg; and the curve was determined as non-linear. The experiment was done on horizontal abduction (temporal) motion only while the horizontal adduction (nasal) motion was assumed symmetric.

In [95], the tissues stiffness were studied again using a non-invasive techniques on normal subject not strabismus patients, to be more representative of the normal eye behaviour. The mean tissues stiffness restraining the globe movement in the nasal direction (1.05 gm/deg) was reported as 11% greater than in the temporal direction (0.94 gm/deg). These measurements were done with all muscles intact and right eye fixed at a target at 30 deg to the right, while the left eye is moved with forceps from right to left and back. Thus, the stiffness of the agonist muscle and the antagonist muscle contribute to the mean tissue stiffness measured.

B. EOMs IN COMPARISON TO SKELETAL MUSCLES

EOMs are identified as the fastest and the most fatigue resistant muscles [98], [99]. EOMs are very fatigue resistive because, on average, an eye makes at least 100,000 saccades per day. Saccadic movements make EOMs the fastest contracting muscles as they also have more mitochondria and a higher metabolic rate than other skeletal muscles. In addition to that, eye muscle fibers are richly innervated since each motoneuron innervates only 10-20 muscle fibers [51].

EOMs are bilaminar, that is they consist of two layers of different fiber type content [99], [100]. The unique constituent fiber types of EOMs make it difficult to draw exact similarities to skeletal muscle fiber types. The orbital layer lay close to the periorbital and orbital bone. The global layer lay close to the eye-globe and optic nerve. There is clear evidence that there is no true slow twitch fiber types in the six EOMs.

The orbital fibers are 80% singly-innervated, which are the most fatigue-resistant skeletal muscle fiber type. It is the main factor contributing to the sustained force levels, since EOMs tension levels never fall beyond 8-12 grams [92]. Thus, there is no rest position for EOM; they are always innervated even at the primary position. The rest of this layer of fibers are multiply-innervated. They also show evidence of structural variation along its length, where the central part shows moderately fast twitch fiber profiles while the proximal and distal ends show slowly contracting fiber profiles.

The global fiber layer can be divided into four fiber types. More than 30% are singly innervated fibers, that are fast twitched and highly fatigue resistant. Approximately 25% are singly innervated fast twitch fiber type but with intermediate fatigue resistance. Another 30% are singly innervated fast-twitch fibers and have low fatigue resistance with high anerobic metabolic capacity. They are used only sporadically. The rest of the fibers are multiply innervated that exhibits a slow graded, non-propagated response on activation and they are highly fatigue resistant [99].

All fiber types participate in every type of movement, the activity of a single motor unit is correlated to eye position regardless of the eye movement system that attained this eye position [99], [100]. This does not follow the proved correlation between fiber types and various movement systems found in skeletal muscles [101], [102].

C. PULLEY THEORIES

The role of the connective tissue, known as pulleys in the kinematics of eye rotation has been subject to controversial argument for some time. We can divide the development and progress of the pulley theory into four consequent theories; classical, traditional, passive pulley and finally active pulley theory [103].

1) CLASSICAL THEORY

In the work of Boeder [104] and Krewson [105], the rectus EOMs were assumed to be constrained only at its origin and moving in a straight line to its tangential point on the globe then to its insertion point. However, in his mathematical model to calculate muscle forces and innervation at different gaze positions, Robinson [71] concluded that the classical model cannot be correct because it might cause muscle side-slip during rotation which was unrealistic and never observed in surgeries.

2) TRADITIONAL THEORY

Miller and Robinson [49] built SQUINT, a computer model that calculates the static mechanics of the human eye, built as an extension to Robinson mathematical model [71]. They attributed the restrained side-slip to elastic connective tissues surrounding the eye-globe and the EOMs. This model assumed the axis of rotation of the eye-globe fixed in the orbit and assuming that the brain was responsible for the kinematics that obey Listing's Law.

3) PASSIVE PULLEY THEORY

Using different imaging techniques, it was evident that the posterior section of rectus EOMs were stabilised with respect to the orbit with gaze change. An intermuscular harness or pulley was hypothesised to control muscle side-slip, this was proven by observation during surgery [106], [107]. This theory made the axis of rotation a function of gaze. The passive pulley effect, shown in Fig. 5, describes how correctly located pulleys could cause muscle axis to incline by half the angle of rotation which satisfies Listing's Law, thus, eye movement looks commutative to the brain when moving from the primary position to a secondary gaze position. However, passive pulley theory fails in tertiary positions.

Pulley location and stability were studied further from rectus EOMs muscle path inflection with gaze change in secondary position [65], [108]. *Orbit^{TM}* gaze mechanics simulation software [109], [110] based on SQUINT, implemented passive pulleys. SEE++ [111], [112] was an extension of *Orbit^{TM}*, which simulated the static behaviour of the eyes for strabismus surgeries.

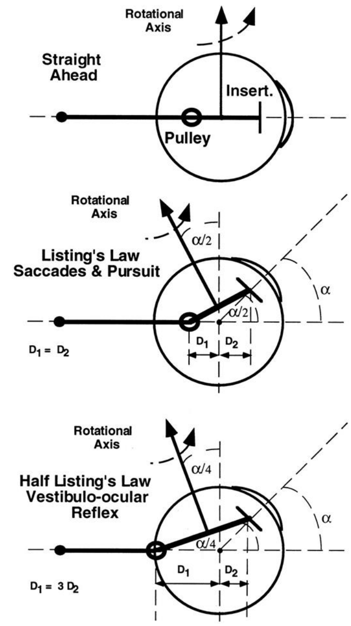


FIGURE 5. Effect of pulleys on the rotational axis of horizontal rectus EOMs. Top: eye in looking straight ahead. Middle: Eye in secondary position during saccades/pursuit eye movements with α as elevation angle, D_1 as the distance from the pulley to the globe center and equal to distance D_2 from the insertion to the globe center. The rotational axis of the EOM is inclined posteriorly by approximately $\alpha/2$, satisfying the Listings half-angle rule. Bottom: During VOR, the half-Listings quarter-angle rule can be satisfied if posterior displacement of the pulley occurs such that $D_1 = 3D_2$. [97].

4) ACTIVE PULLEY THEORY

The Active Pulley Hypothesis (APH) [97] stated that the connective tissues, constituting the pulleys, work as the functional origin of the rectus EOMs. Histologic studies showed that the orbital layer of rectus EOMs are inserted on the pulley not the eye-globe [99], [113]. Thus, the global layer (GL) of the EOMs are the main rotator of the globe, while the orbital layer (OL), which inserts on the pulley, influences the rotational axis by linear antero-posterior translation of the pulley location that is gaze dependent. In tertiary gaze positions, the EOM path inflections obtained from magnetic resonance imaging (MRI) supported APH and thus, the hypothesis that rectus pulleys shift ocular rotation axis to attain commutative behaviour of the ocular motor was proven [96].

Kono *et al.* [96] defined two versions of APH; Coordinated APH and Differential APH. The Coordinated APH stated that the rectus pulley location changes such that the distance from the pulley to the eye-globe center is equal to distance from the eye-globe to the insertion point of the muscle, thus, obeying the half-angle rule of Listing's law, and implementing a linear commutative ocular motor plant as shown in Fig. 5. The entire EOM, in this hypothesis, contract in coordination. The Differential APH stated that, to account for VOR and convergence not obeying Listing's law, there is differential innervation by brainstem in rectus OLs and GLs. That implies that OL and GL are mechanically independent which was denied by Lennerstand *et al.* [93], [96] and thus, this notion of strong differential APH was abandoned. Another proposal for the differential APH, known as weak differential APH [103], hypothesised that instead of completely independent innervation, a gradual change of innervation between different layers of the EOM. Differential APH is still being investigated according to Millers [103].

IV. VISUAL FATIGUE AND VIRTUAL ENVIRONMENTS

Fatigue has been defined mostly relative to muscle performance [114]–[116] or to decreased mental performance [117]. Fatigue has also been associated with nearly all important diseases [118]. It has been measured through subjective evaluation and objective performance determinants [119].

In the case of muscle fatigue, muscle soreness from overuse is only temporary, and with repeated exercise the muscle fatigue is gradually eliminated. In eye muscles, the same case can be assumed since eye movement is habitual from birth which eliminates symptoms of muscle fatigue [120]. However, ocular muscles are closely coupled with the innervation communicated by the brain and thus, they experience fatigue quiet differently than skeletal muscles. This section explains the fatigue experienced by ocular muscles and reveals its relationship with mental fatigue.

A. VISUAL FATIGUE

Visual fatigue can be attributed to fatigue of the retina or coordination fatigue according to Jackson [120]. Retinal fatigue is accompanied by lowered visual acuity. It is increased by great difference in the intensity of objects at which the eye gaze is pointed [120]. The coordination fatigue is related to the neural control of the six EOMs. An elaborate system of coordination between the EOMs of both eyes and the retina is required to move the eye and satisfy the conditions for visual acuity. The extraocular muscles (EOMs) are highly fatigue-resistant due to their fiber structure [99]. Therefore, it had been considered that visual fatigue is not attributed to muscular fatigue but to mental fatigue (or tiredness) [121], [122]. Thus, determining the neural control of the EOMs can be an important determinant of fatigue levels.

An important point noted in [120] is that normal visual fatigue rarely comes into consciousness in normal conditions; only in the cases of long continued or repeated excessive fatigue does the brain translate it into discomfort or pain.

Therefore, subjective evaluation of fatigue may not be an accurate measure of the level of fatigue that may have manifested already. Other physiological determinants like eye movement can be used to better determine fatigue levels in an objective manner.

In studies of subjective visual fatigue associated with visual tasks on 3D displays and HMDs [123]–[126], they identified symptoms related to visual fatigue, motion sickness and ocular surface. Visual fatigue related symptoms include double vision, difficulty in focusing and/or eye strain while motion sickness related symptoms include headache, nausea, dizziness and/or drowsiness. Ocular surface-related symptoms included watery eyes, sting and eyeache.

Visual fatigue has a significant effect on eye movement kinematics. Saccadic speed decrease and increase in fixation duration has been found during performing long tasks and in sleep deprivation trials [31], [37], [38]. Bahill *et al.* identified the different types of saccadic movements and attributed glissadic undershooting and multi-step saccades to fatigue [127], [128]. An undershooting occurs when the eye tries to fixates at a new point but fails short of reaching the target. A glissadic eye movement is a gradual sliding movement of the eye to reach the target. A multi-step or overlapping saccade is when two or more closely spaced saccades follow each other to reach the target. These types of saccades were reported in sleepy or fatigued subjects, also in drug intoxication in addition to ocular diseases [31], [38], [39], [127], [128].

B. DETERMINANTS OF VISUAL FATIGUE

Different determinants were used to measure visual fatigue and discomfort. Eye blinking rate (BR), electrooculography (EOG) or electroencephalography (EEG) biosignals, and most commonly, subjective evaluation were used [29]–[35], [123], [129]. Also, combinations of these determinants and others were correlated to determine visual fatigue [36]. The disadvantages of measurements based on bio-signals include the subject's discomfort during experiments due to sensors and also the fact that bio-signals are highly susceptible to artefacts caused by muscular movements.

The rapid development and increased performance of eye trackers made fatigue detection by eye movement a more inviting method. It can be an efficient and easy-to-use tool for visual ergonomics [130]–[132]. Real-time driver vigilance has been detected through eye-movement, by determining blink rate and blink duration [133]–[138]. When combined with ocular biomechanics, eye trackers and VR embedded eye-trackers determines more than just blink parameters of eye movement, which can be used for quantitative measurement of fatigue.

Finally, visual fatigue is not a muscular fatigue but more related to mental fatigue. However, the use of tools related to brain imaging such as EEG, EOG or other bio-signals has the disadvantage of having to be worn and thus, hinders normal behaviour. Moreover, the complexity of such signals extremely exceeds eye movement signals. That is why using biomechanical analysis of eye movements, which can be captured through remote eye-trackers or eye-trackers embedded inside HMDs, is a very inviting and exciting solution. The biomechanical analysis will convert eye movement into muscular forces that are further converted into neural control.

C. VERGENCE ACCOMMODATION CONFLICT

Visual fatigue is one of the main factors of discomfort in VE which is caused mainly by the vergence-accommodation conflict (VAC) [12], [15], [140], [141]. VAC occurs when

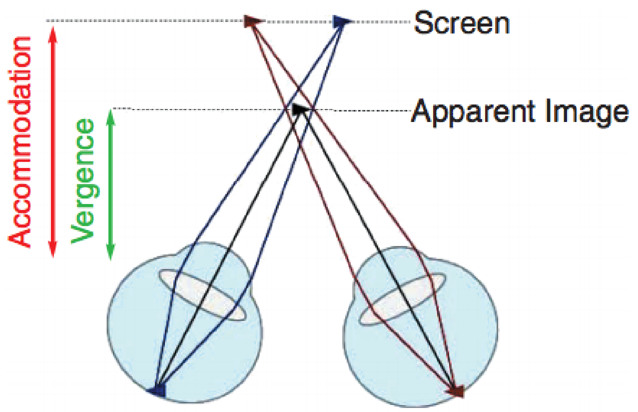


FIGURE 6. Accommodation-vergence conflict (VAC) occurs in stereoscopic displays when the accommodation distance mismatch the rendered image distance. The eyes converge to deblur a near image whereas a different depth is perceived due to screen position [139].

the perceived depth and virtual depth mismatch, as illustrated in Fig. 6, due to 3D rendering.

As the object of interest moves nearer/further, vergence eye movement is induced to return the object to the center of the retinal for a focused image, determining the new distance of the object. Vergence is stimulated, also, by binocular disparity, that helps the brain perceives depth [140]. Vergence stimulate accommodation to change the power of the lens by increasing/decreasing the light intake, to accommodate the change in distance [140], [142]. Accommodation can, also, be stimulated without vergence by a blurred image, thus vergence is not a necessary condition [143]. In addition, accommodation can induce vergence, too [144].

The two responses are coupled by a feedback loop [140], [145], making them work as secondary cues for each other. Thus, the conflict between depths perceived and 3D rendered affects our binocular ability and with time causes visual fatigue.

D. VIBRATION INDUCED VESTIBULO-OCULAR REFLEX

Motion during immersion is another factor causing discomfort. Vibrational motion in virtual environments can increase the level of discomfort as experienced while using helmet mounted displays (HeMDs) over rough terrains [19], [146], [147]. This affects situational awareness and overall performance [148].

As a moving object is being tracked, the eyes move in smooth pursuit. Smooth pursuit movement dominates, even when low frequency vibration of less than 1 Hz of the head occurs. However, when the vibration frequency increases, VOR takes over, causing an opposite eye movement. VOR is activated mainly to decrease retinal blur due to vibration [148].

HeMDs display are stabilised with respect to the head due to head tracking mechanisms, therefore when VOR is activated, the display is displaced with respect to eyes movement. Consequently, visual acuity and visual performance decrease and thus visual fatigue occurs [149]–[152].

E. VISUALLY-INDUCED MOTION SICKNESS

Visually induced motion sickness (VIMS) is induced not by physical movement but due to viewing a moving scene. VIMS is triggered by visual stimulus while physical movement may be limited or completely absent. It is related to illusory self-motion, described in Fig. 7, which is accompanied with mismatching body motion [20], [21]. VIMS during motion simulations such as flight simulators is called simulator sickness [153] while VIMS caused in virtual environments are called cybersickness. Since some types of movement can be provided in virtual environment and simulators thus sickness induced maybe through visual stimulus and non-visual stimulus as physical movement or haptic feedback [154]–[158]. VIMS symptoms, are similar to motion sickness, however less severe. While, fewer people are affected by simulator sickness [159], it can disrupt the virtual scenario in critical applications such as military and medical training. VIMS symptoms include drowsiness, cold sweat, nausea and oculo-motor disturbances [160]–[162]. Oculo-motor disturbance is associated with VIMS but not with motion sickness [23], [163]. Stanney [23] reported that simulation sickness causes more oculomotor disturbance while cybersickness causes more disorientation symptoms. Both symptoms are closely related to the optokinetic reflex of eye movement.

Optokinetic reflex is a fast eye movement in response to large moving visual scenes, which may induce the perception of self-motion and thus cause VIMS. When the head is bent out of the axis of rotation of the rotating visual scene, optokinetic motion sickness occur [22] due to Psuedo-Coriolis effect (PCE). Coriolis effects (CE) is the a motion sickness induced due to bending of the head during physical body rotation [164]. On the other hand, the Psuedo-Coriolis effect (PCE) occurs as a result of head bending without physical rotation but with only perceived self-rotation due the rotation of the visual scene about a vertical axis around a stationary observer [22]. Thus, PCE can cause motion sickness in virtual environments due to optokinetic response induced by perceived self-motion and head bending.

V. BIOMECHANIC MODELS FOR OCULAR MOTILITY

Biomechanical analysis can be a useful tool for virtual environments ergonomics. Biomechanical analysis and simulation has been used in ergonomic evaluation of various activities such as mining, sports and rehabilitation among others [154], [166], [167].

As discussed earlier, visual fatigue is not related to muscular fatigue but rather to mental fatigue, due to overloading of the brain with conflicting signals from the ocular and other related systems like the vestibular system. That is why determining the neural control of EOMs during immersion, through biomechanical analysis, can be an appealing and new method to objectively define fatigue. Fatigue will be related to change in eye kinematics during immersion. Also, the effect of neck muscles fatigue and VOR on fatigue levels

TABLE 3. Comparison between different ocular biomechanical models in literature.

Model	Description	Simulations Performed	Pulleys	Integrable to human models
Robinson (1975) [71]	It used mechanical force equilibruim equation to calculate innervation of EOM at specified gaze position	Static Simulations Only	None	No
SQUINT (1984) [49]	It was an extension of Robinson work. It solved the innervation and position problem using an iterative technique with the mechanical equilibruim equation.	Static Simulations Only	None	No
SEE++ (2005) [112]	It presented a biomechanical model with passive pulleys. It was mainly designed to predict surgical outcomes.	Static Simulations Only	Passive Pulleys	No
Pascolo et al. (2009) [170]	It presented a mechanical model of the human eye to estimate muscular force. It had a simplified representation of the EOMs	Dynamic Simulations	None	No
Wei et al.(2010) [86], [171]	It presented a model to simulate 3D eye movements	Dynamic Simulation	Passive & Active Pulleys	No
Gao et al. (2014) [84], [85], [169]	It used static mechanical equilibruim equation to calculate the initial tension and contractile force of EOMs. In addition, the effect of passive versus active pulleys on muscle forces	Static Simulations Only	Passive & Active Pulleys	No
OpenEyeSim (2016) [50]	It is a 3D biomechanical model of the EOMs. It simplified the model for faster simulation by not adding active pulleys	Dynamic Simulation	Passive Pulley	Yes
Iskander et al. (2017) [45]	Ocular model added to a human head and neck model to simulate eye-head coordination during smooth pursuit	Dynamic Simulations	Passive & Active Pulleys	Yes

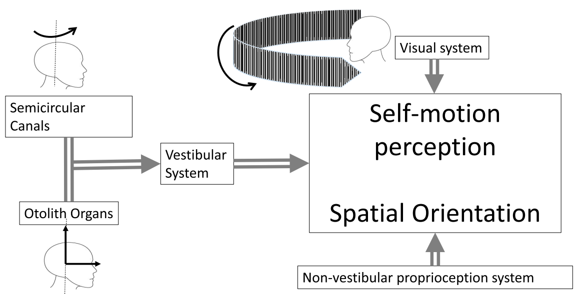


FIGURE 7. The different systems that contribute to the perception of self-motion are illustrated. The semicircular canals and the otolith organs are parts of the vestibular system that detect neck rotation and translation. The eyes and the visual system are stimulated by motion of large scenes. In addition, non-vestibular propioceptive inputs and motor control commands from the limbs and truck affects our spatial orientation. Mismatch between these coupled systems are attributed to causing motion sickness symptoms [165].

can be studied by biomechanical analysis of gait and body postures during immersion. The use of human body models augmented with ocular biomechanical models will provide an efficient, non-invasive method to detect and quantify visual fatigue. It can also, simulate different scenarios of immersion, to calculate the optimum posture with minimum discomfort.

Biomechanical simulation and analysis can aid in finding new methods to mitigate the different types of motion sicknesses induces in virtual environments. This will help ensure the quality of experience. Biomechanical analysis of coordinated eye-neck movement in moving/rotating visual scenes can be a promising method to asses postures that may mitigate sickness for susceptible users. Investigation of speed and location of visual field has been done [22], [168] but further investigation of their effect on eye movement and level of sickness can be done through biomechanical analysis of the eye-head movement.

Various hypotheses and theories were presented to explain the kinematics of eye movement and the neural control role in adopting them. In this section, we will present different types of ocular biomechanic models in the literature and then validation methods are discussed. A summary of the ocular models development is presented in Table 3.

A. STATIC MODELS

The first attempt to use mechanical force equilibrium equations to calculate innervation of extraocular muscles in a specific position was presented by Robinson [71] and extended into the SQUINT software [49]. The study mathematically approximated the length-tension curves [89], and used an iterative method to solve the two problems, the innervation problem and the position problem such that the equilibrium equation in Eq. 3 is satisfied. The innervation problem, assuming a normal eye, calculates the forces and innervation of the six EOMs that will hold the eye globe at a specific gaze position. The position problem uses the calculated forces and innervation of the muscles to study abnormal pathological cases by predicting eye position in those cases and comparing deviations from the normal case. SQUINT extended the derived muscle response curves to include the slack region where the muscle shortened sufficiently while exerting no force. It also included the leash region where the muscle is stretched sufficiently while undergoing a dramatic increase in stiffness. The mechanical equilibrium equation can be expressed as

$$P + \sum_{i=1}^{6} F_i m_i = 0, \tag{3}$$

where P is the passive force created by non-muscular structures that opposed the globe rotation and act to return the globe to its primary position, m is a unit vector indicating direction of force F and i indicates one of the six muscles. F should be values presenting moments of force but since the moment arm is the radius of the eye-globe, which is equal in all terms, it has been ignored and now all terms present forces. SEE++ [111], [112] was an extension of $Orbit^{TM}$, which simulated the static behaviour of the eyes for strabismus surgeries.

Gao *et al.* [84], [85], [169] used static mechanical equilibrium equation to calculate the initial tension of EOMs in the primary position, contractile forces of EOMs and effect of passive and active pulleys. Their results were in accordance with experimental results.

B. DYNAMIC MODELS

Passive Pulley location and stability determined in [65], [96], and [108] were used by Pascolo and Carneil [170] and Wei *et al.* [86], [171] to produce models that included pulleys. In [86] and [171], dynamic simulation of the eye during saccades was presented using a strand-based EOM model using a two-element Hill-type muscle model. The model incorporated active pulleys but it was not added to a human body model, making it difficult to simulate coordination between eye movement and human posture. Consequently, investigation of vestibular effect on eye movement is not possible either.

C. EYE-BODY COORDINATION MODELS

The recent advances of portable eye tracking, motion capture and bio-signal acquisition systems ushered the need for ocular biomechanic models which are integrable in skeletal biomechanic models.

OpenEyeSim [50] presents a biomechanical model implemented in OpenSim that aims at developing models of the joint learning of visual representations and eye-movement control. However, the model did not implement active pulleys, which makes the kinematic and innervation results unrealistic as the active pulleys change the direction of pull of muscles with orientation change. According to the active pulley hypothesis, the change of eye gaze in tertiary positions causes a displacement of the pulley location causing a change in the length of the muscle and thus, the total force produced will be different than the total force produced if the pulley location did not change. However, passive pulley were used for faster simulations with reduced accuracy in tertiary gaze positions. The inverse dynamics techniques provided in OpenSim was not used, but a black-box optimization technique [172] that is based on a reward function that favours closer kinematics to desired while lowering activation levels for a lower metabolic cost.

In [45], an ocular model added to a human head and neck model [173] is presented. The ocular model had EOMs modelled with active moving pulleys. Simulation of smooth pursuit with head coordination was performed with very low RMSE in tracking the desired kinematics. It can be easily used to analyse eye and body movement during immersion.

D. VALIDATION OF OCULAR BIOMECHANIC MODELS

Ocular biomechanic models can be validated using inverse and forward dynamics and by testing whether or not the model follows Listing's law. There are advantages and drawbacks for both validation methods. While the first validation method derives the overall error in the model in any gaze and body posture, it is prone to noise and synchronisation errors produced by the hardware. On the other hand, the second validation method does provide a solid mathematical background, yet it only validates the model in terms of torsional error in secondary and tertiary gaze positions [78]. This is valid in fixations only, as it was found that the eyes will obey Listing's Law to a lesser extent (only approximately) during saccades, smooth pursuit and blinks [79], [174].

Similar to skeletal biomechanic models, validating ocular biomechanic models can be achieved by performing inverse dynamics followed by forward dynamics using captured motion. In the inverse dynamics step, the captured eye gaze trajectories are analysed to derive muscle activation signals. In the forward dynamic step, the derived muscle activation signals are used to animate the simulated eye to produce an estimate of the captured gaze trajectories. The difference in captured and simulated trajectories define the error produced by the ocular model [175]. Additionally, the derived muscle can be further validated against muscle activation signals collected via Electromyography (EMG). However, recording EMG signals of EOMs is an invasive procedure that needs advanced medical expertise because it involves the use of needle EMGs electrodes in contrast to the surface EMG electrodes commonly used. This is an invasive procedure and imposes discomfort to subjects [176]–[178].

According to Listing Law's, during fixations in primary and secondary positions, the torsion should be zero for normal eyes. In tertiary position, the torsion should obey Listing's equation as discussed in Section II-D. Validation of ocular models by simulating fixations at different secondary positions by varying the horizontal/vertical angles. Using these desired horizontal and vertical kinematics, we can use inverse dynamics and validate that the achieved kinematics keeps torsion approximately zero.

Using eye movement systems other than fixation, will be difficult to validate since from previous experiments, it was found that the eye only, approximately, obey Listing's law in smooth pursuit, saccades and blinks [78], [79], [174].

VI. CHALLENGES OF USING BIOMECHANICAL ANALYSIS IN VIRTUAL ENVIRONMENTS ERGONOMICS

There are three major challenges hindering the use of ocular models that is integrable within musculoskeletal biomechanics models. The first challenge is the disparity in movement nature of ocular and skeletal motility. The second challenge is the wider dynamic range of forces and joint angles produced by skeletal motion in comparison to ocular motion. The difference in the sampling rate needed when capturing coordinated eye and body movement represents the final challenge.

A. DISPARITY IN TYPE OF MOVEMENT

The optimisation techniques, used in biomechanical analysis to derive activation levels of the muscles, are mainly based on minimising the activation level such that the force generated is within tolerance from the force required as in static optimisation [179]–[181] or minimising activation levels such that desired acceleration is achieved within tolerance as in compute muscle control (CMC) [182]–[184].

In all the eye movements, the rapidness to stabilize the image is the main target. Velocity may increase or decrease, according to object of interest being tracked, by means of closed loop feedback system when lag between eye velocity and object velocity cause retinal image slip.

When investigating the velocity and acceleration characteristics of the six different functional eye movement systems that have been described in Section II-B, we can find the following. In smooth pursuit, the eye follows smoothly a moving object which might accelerate or decelerate [28], [51]. In saccades, there is an initial instantaneous acceleration then nearly zero velocity is maintained [28], [51]. In fixation, the eye fixates at a point with drifts and micro-saccades of less than 0.5 deg [28], [51]. In vergence, in order to hold the image of a single object simultaneously on both foveae, the eyes move in directions opposite to each other. It takes from 150-200 msec [28], [51]. In vestibulo-ocular reflex (VOR), eye movement follows head velocity by 90% in horizontal and vertical VOR but to a lesser degree in case of torsional VOR [28], [59]. Thus, we can safely imply that most eye movements has a very rapid instantaneous acceleration and most commonly a constant or linearly increasing or decreasing velocity to sustain clear vision [28], [51]. Therefore, movement of eye is very rapid, in contrast to the skeletal motion which rely on slow accelerating motion. This means that the inverse dynamics optimisation algorithms designed for postural movements may not be suitable for ocular movements. Also, optimisation techniques relying on acceleration error as a constraint to converge, as in the case of compute muscle control method, may not be suitable for eye movement simulation.

B. DYNAMIC RANGE OF FORCES AND JOINT ANGLES

The second challenge is the difference in the dynamic range of forces and joint angles between ocular and skeletal muscles. For example, it is acceptable for skeletal models to have a joint angle error of 4 deg, as in the latest published musculoskeletal human body model [47], while the ocular models must maintain a maximum 0.5 deg error to maintain an acute vision. This, in return, causes the optimisation of inverse dynamics equations to converge prematurely and produce a higher error in ocular simulation results.

Eye movements have special requirements that need to be considered when modelling the ocular system. For visual acuity and clarity, the object's image has to fall on the center of the retinal fovea with an accuracy of 0.5 deg. Visual acuity may decrease to 50% if image was 5 deg from the foveal center [28]. Therefore, kinematic tracking error should be very low, in order to correctly track the line of gaze and eye orientation.

Static optimisation [179]–[181], as an inverse dynamics method, is based on the moment of force desired to accomplish the movement task. This can be a solution to the issue introduced with the compute muscle control method since using acceleration error does not fulfill the condition for accurate fixation of gaze. However, static optimisation was designed to get optimized activation levels for gait motion. The moment of force produced in gait motion is in the order of hundreds of N.m which is not the case for eye movement. EOMs produce moments of force in the order of $10^{-3}N.m$ since their produced forces are in the range of mN and the raduis of the eye-globe is approximately 12 mm.

C. COORDINATED EYE-BODY MOTION CAPTURE CHALLENGE

Finally, there is a need to capture eye-movement data with very high sampling rate. With the availability of different motion capture devices and techniques, human movement has been captured and analysed in different scenarios. However, there is still a scarcity of datasets of coordinated eye and body movement during immersion. It is achievable now with embedded eye-trackers in VR headsets available. In normal gait movement, 60 or 120 Hz are used, however, saccadic eye movement velocity can reach 900 degree/second. Thus, a sampling rate of above 200 Hz is recommended.

In addition synchronisation between the motion capture devices and the eye trackers should be achieved. Synchronisation ensures that the analysis of the coordinated eye-head movement is valid.

VII. CONCLUSION

This paper presented a literature review on the ocular system and ocular biomechanics. Different ocular models have been reviewed from the first mathematical model presented by Robinson [71] till models created in OpenSim [45], [50]. We highlighted the potential use and challenges of using ocular biomechanical analysis to assess visual fatigue. It can be used as an ergonomic tool for assessing virtual environments.

While research in VR hardware has advanced rapidly in the past few years, users are still experiencing VR-related visual fatigue attributed to VAC and motion during simulation. Visual fatigue is attributed to mental fatigue and neural control more than muscular fatigue. This is due mainly to the fatigue-resistive nature of extraocular muscles. Different determinants have been used to measure fatigue, including eye movement. With the advent of remote eye-trackers and eye-trackers embedded in VR headset, it became easy to record eye movement in a seamless, non-intrusive way in contrast to the EEG- and EOG-based methods. EEG and EOG signals suffer from noise artefacts and require noise cancellation and source isolation algorithms.

We presented the challenges of using eye movement signals in biomechanical analysis to measure visual fatigue during immersion. Incorporating ocular and skeletal kinematics is rapidly gaining momentum in this area of research. However, it is facing few challenges due to the wide difference in dynamic range of motion and muscle forces of ocular and skeletal muscles which, in return, affects the available biomechanics modelling systems and causes it to converge prematurely. Shortage of data is also another challenge that needs highlighting. It has been noted that there is a scarcity of datasets of coordinated eye and body movement during immersion. Such data will be useful for the assessment and quantification of visual fatigue in virtual environments. Validation of ocular biomechanic models is achievable using inverse and forward dynamics. Yet, the ability of models to follow Listing's law is a critical step in order to derive kinematically sound biomechanic models.

REFERENCES

[1] J. O. Bailey and J. N. Bailenson, "Considering virtual reality in children's lives," *J. Children Media*, vol. 11, no. 1, pp. 107–113, 2017.

[2] M. Limniou, D. Roberts, and N. Papadopoulos, "Full immersive virtual environment CAVE in chemistry education," *Comput. Edu.*, vol. 51, no. 2, pp. 584–593, 2008.

[3] K. L. Dean *et al.*, "Virtual explorer: Interactive virtual environment for education," *Presence, Teleoper. Virtual Environ.*, vol. 9, no. 6, pp. 505–523, 2000.

[4] J. McComas, P. Pivik, and M. Laflamme, "Current uses of virtual reality for children with disabilities," *Stud. Health Technol. Informat.*, vol. 58, pp. 161–169, Jan. 1998.

[5] J. M. Loomis, J. J. Blascovich, and A. C. Beall, "Immersive virtual environment technology as a basic research tool in psychology," *Behavior Res. Methods, Instrum., Comput.*, vol. 31, no. 4, pp. 557–564, 1999.

[6] D. Freeman *et al.*, "Virtual reality in the assessment, understanding, and treatment of mental health disorders," *Psychol. Med.*, vol. 47, no. 14, pp. 2393–2400, 2017.

[7] R. Pausch, T. Crea, and M. Conway, "A literature survey for virtual environments: Military flight simulator visual systems and simulator sickness," *Presence, Teleoper. Virtual Environm.*, vol. 1, no. 3, pp. 344–363, 1992.

[8] J.-L. van Gelder, C. Nee, M. Otte, A. Demetriou, I. van Sintemaartensdijk, and J.-W. van Prooijen, "Virtual burglary: Exploring the potential of virtual reality to study burglary in action," *J. Res. Crime Delinquency*, vol. 54, no. 1, pp. 29–62, 2017.

[9] J. Dascal *et al.*, "Virtual reality and medical inpatients: A systematic review of randomized, controlled trials," *Innov. Clin. Neurosci.*, vol. 14, nos. 1–2, p. 14, 2017.

[10] S.-Y. Hsu, T.-Y. Fang, S.-C. Yeh, M.-C. Su, P.-C. Wang, and V. Y. Wang, "Three-dimensional, virtual reality vestibular rehabilitation for chronic imbalance problem caused by ménière's disease: A pilot study," *Disab. Rehabil.*, vol. 39, no. 16, pp. 1601–1606, 2017.

[11] T.-A. P. Le and D. C. Beidel, "Psychometric properties of a social skills assessment using a virtual environment," *J. Psychopathol. Behavioral Assessment*, vol. 39, no. 2, pp. 230–240, 2017.

[12] H. Hua, "Enabling focus cues in head-mounted displays," *Proc. IEEE*, vol. 105, no. 5, pp. 805–824, May 2017.

[13] R. E. Stevens, T. N. Jacoby, I. C. S. Aricescu, and D. P. Rhodes, "A review of adjustable lenses for head mounted displays," *Proc. SPIE*, vol. 10335, p. 103350Q, Sep. 2017.

[14] J. Rolland and H. Hua, "Head-mounted display systems," *Encyclopedia Opt. Eng.*, pp. 1–13, 2005.

[15] T. Shibata, "Head mounted display," *Displays*, vol. 23, nos. 1–2, pp. 57–64, 2002.

[16] M. Mon-Williams, J. P. Warm, and S. Rushton, "Binocular vision in a virtual world: Visual deficits following the wearing of a head-mounted display," *Ophthalmic Physiol. Opt.*, vol. 13, no. 4, pp. 387–391, 1993.

[17] M. Mon-Williams, J. P. Wann, and S. Rushton, "Design factors in stereoscopic virtual-reality displays," *J. Soc. Inf. Display*, vol. 3, no. 4, pp. 207–210, 1995.

[18] Tobii Tech. *Tobii Releases Eye Tracking VR Development Kit for HTC Vive*. Accessed: Mar. 20, 2018. [Online]. Available: https://www.tobii.com/group/news-media/press-releases/2017/5/tobii-releases-eye-tracking-vr-development-kit-for-htc-vive/

[19] D. J. Uribe and M. E. Miller, "Eye movements when viewing a HMD under vibration," *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 57, no. 1, pp. 1139–1143, 2013.

[20] B. Keshavarz, H. Hecht, and B. Lawson, "Visually induced motion sickness: Characteristics, causes, and countermeasures," in *Handbook of Virtual Environments: Design, Implementation, and Applications*. 2014, pp. 648–697.

[21] B. Keshavarz, B. E. Riecke, L. J. Hettinger, and J. L. Campos, "Vection and visually induced motion sickness: How are they related?" *Frontiers Psychol.*, vol. 6, p. 472, Apr. 2015.

[22] J. Dichgans and T. Brandt, "Optokinetic motion sickness and pseudo-Coriolis effects induced by moving visual stimuli," *Acta Oto-Laryngol.*, vol. 76, nos. 1–6, pp. 339–348, 1973.

[23] K. M. Stanney, R. S. Kennedy, and J. M. Drexler, "Cybersickness is not simulator sickness," *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 41, no. 2, pp. 1138–1142, 1997.

[24] R. J. Leigh and C. Kennard, "Using saccades as a research tool in the clinical neurosciences," *Brain*, vol. 127, no. 3, pp. 460–477, 2004.

[25] U. P. Mosimann, R. M. Müri, D. J. Burn, J. Felblinger, J. T. O'Brien, and I. G. McKeith, "Saccadic eye movement changes in Parkinson's disease dementia and dementia with Lewy bodies," *Brain*, vol. 128, no. 6, pp. 1267–1276, 2005.

[26] H. J. Kaminski, M. Al-Hakim, R. J. Leigh, M. K. Bashar, and R. L. Ruff, "Extraocular muscles are spared in advanced duchenne dystrophy," *Ann. Neurol.*, vol. 32, no. 4, pp. 586–588, 1992.

[27] H. J. Kaminski and R. J. Leigh, *Neurobiology of Eye Movements: From Molecules to Behavior* (Annals of the New York Academy of Sciences), vol. 956. Cleveland, OH, USA: Univ. Hospitals Cleveland, 2002. [Online]. Available: http://ezproxy.deakin.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-0036233783&site=eds-live&scope=site

[28] R. J. Leigh and D. S. Zee, *The Neurology of Eye Movements*, vol. 90. New York, NY, USA: Oxford Univ. Press, 2015.

[29] C. Chen, K. Li, Q. Wu, H. Wang, Z. Qian, and G. Sudlow, "Eeg-based detection and evaluation of fatigue caused by watching 3DTV," *Displays*, vol. 34, no. 2, pp. 81–88, 2013.

[30] H. Cho, M.-K. Kang, K.-J. Yoon, and S. C. Jun, "Feasibility study for visual discomfort assessment on stereo images using eeg," in *Proc. Int. Conf. 3D Imag. (IC3D)*, Dec. 2012, pp. 1–6.

[31] R. Schleicher, N. Galley, S. Briest, and L. Galley, "Blinks and saccades as indicators of fatigue in sleepiness warnings: Looking tired?" *Ergonomics*, vol. 51, no. 7, pp. 982–1010, 2008.

[32] D. Kim, S. Choi, J. Choi, H. Shin, and K. Sohn, "Visual fatigue monitoring system based on eye-movement and eye-blink detection," *Proc. SPIE*, vol. 7863, p. 786303, Feb. 2011.

[33] J.-H. Yu, B.-H. Lee, and D.-H. Kim, "EOG based eye movement measure of visual fatigue caused by 2D and 3D displays," in *Proc. IEEE-EMBS Int. Conf. Biomed. Health Informat. (BHI)*, Jan. 2012, pp. 305–308.

[34] P. A. Howarth and P. J. Costello, "The occurrence of virtual simulation sickness symptoms when an HMD was used as a personal viewing system," *Displays*, vol. 18, no. 2, pp. 107–116, 1997.

[35] S. Yano, S. Ide, T. Mitsuhashi, and H. Thwaites, "A study of visual fatigue and visual comfort for 3D HDTV/HDTV images," *Displays*, vol. 23, no. 4, pp. 191–201, Sep. 2002.

[36] J. W. Bang, H. Heo, J.-S. Choi, and K. R. Park, "Assessment of eye fatigue caused by 3D displays based on multimodal measurements," *Sensors*, vol. 14, no. 9, pp. 16467–16485, 2014.

[37] D. Cazzoli, C. A. Antoniades, C. Kennard, T. Nyffeler, C. L. Bassetti, and R. M. Müri, "Eye movements discriminate fatigue due to chronotypical factors and time spent on task—A double dissociation," *PLoS ONE*, vol. 9, no. 1, p. e87146, 2014.

[38] K. Hirvonen, S. Puttonen, K. Gould, J. Korpela, V. F. Koefoed, and K. Müller, "Improving the saccade peak velocity measurement for detecting fatigue," *J. Neurosci. Methods*, vol. 187, no. 2, pp. 199–206, 2010.

[39] C. Diaz-Piedra, H. Rieiro, J. Suárez, F. Rios-Tejada, A. Catena, and L. L. Di Stasi, "Fatigue in the military: Towards a fatigue detection test based on the saccadic velocity," *Physiol. Meas.*, vol. 37, no. 9, p. N62, 2016.

[40] C. Berger and A. Mahneke, "Fatigue in two simple visual tasks," *Amer. J. Psychol.*, vol. 67, no. 3, pp. 509–512, 1954.

[41] S. Iwaki and N. Harada, "Mental fatigue measurement based on the changes in flicker perception threshold using consumer mobile devices," *Adv. Biomed. Eng.*, vol. 2, pp. 137–142, Feb. 2013.

[42] P. A. Snell, "An introduction to the experimental study of visual fatigue," *J. Soc. Motion Picture Engineers*, vol. 20, no. 5, pp. 367–390, 1933.

[43] E. Simonson, "Measurement of fusion frequency of flicker as a test for fatigue of the central nervous system," *Ind. Hygiene Toxicol.*, vol. 23, pp. 83–89, Feb. 1941.

[44] S. L. Delp *et al.*, "OpenSim: Open-source software to create and analyze dynamic simulations of movement," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 11, pp. 1940–1950, Nov. 2007.

[45] J. Iskander, M. Hossny, and S. Nahavandi, "Simulating eye-head coordination during smooth pursuit using an ocular biomechanic model," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2017, pp. 3356–3361.

[46] K. R. S. Holzbaur, W. M. Murray, and S. L. Delp, "A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control," *Ann. Biomed. Eng.*, vol. 33, no. 6, pp. 829–840, 2005.

[47] A. Rajagopal, C. L. Dembia, M. S. DeMers, D. D. Delp, J. L. Hicks, and S. L. Delp, "Full-body musculoskeletal model for muscle-driven simulation of human gait," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 10, pp. 2068–2079, Oct. 2016.

[48] E. M. Arnold, S. R. Ward, R. L. Lieber, and S. L. Delp, "A model of the lower limb for analysis of human movement," *Ann. Biomed. Eng.*, vol. 38, no. 2, pp. 269–279, Feb. 2010.

[49] J. M. Miller and D. A. Robinson, "A model of the mechanics of binocular alignment," *Comput. Biomed. Res.*, vol. 17, no. 5, pp. 436–470, 1984.

[50] A. Priamikov, M. Fronius, B. Shi, and J. Triesch, "OpenEyeSim: A biomechanical model for simulation of closed-loop visual perception," *J. Vis.*, vol. 16, no. 15, p. 25, 2016.

[51] A. M. F. Wong, *Eye Movement Disorders*. London, U.K.: Oxford Univ. Press, 2008.

[52] R. O'Rahilly and F. Müller, *Basic Human Anatomy: A Regional Study of Human Structure*. Philadelphia, PA, USA: Saunders, 1983.

[53] G. K. Von Noorden and E. C. Campos, *Binocular Vision and Ocular Motility*. St. Louis, MO, USA: Mosby, 2002.

[54] J. Malmivuo and R. Plonsey, *Bioelectromagnetism: Principles and Applications of Bioelectric and Biomagnetic Fields*. New York, NY, USA: Oxford Univ. Press, 1995.

[55] R. C. Augusteyn, D. Nankivil, A. Mohamed, B. Maceo, F. Pierre, and J.-M. Parel, "Human ocular biometry," *Experim. Eye Res.*, vol. 102, pp. 70–75, Sep. 2012.

[56] N. A. Dodgson, "Variation and extrema of human interpupillary distance," *Proc. SPIE*, vol. 5291, pp. 36–46, May 2004.

[57] L. R. Young and D. Sheena, "Survey of eye movement recording methods," *Behav. Res. Methods Instrum.*, vol. 7, no. 5, pp. 397–429, Jul. 1975.

[58] D. A. Robinson, "Control of eye movements," in *Handbook of Physiology: The Nervous System*. vol. 2. Bethesda, MD, USA: APS, 1981, pp. 1275–1320.

[59] D. E. Angelaki, "Eyes on target: What neurons must do for the vestibuloocular reflex during linear motion," *J. Neurophysiol.*, vol. 92, no. 1, pp. 20–35, 2004.

[60] C. Rashbass and G. Westheimer, "Disjunctive eye movements," *J. Physiol.*, vol. 159, no. 2, pp. 339–360, 1961.

[61] H. V. Helmholtz, "Physiological optics," in *Optical Society of America*, vol. 3. Pennsylvania, PA, USA: Univ. of Pennsylvania, 2001. [Online]. Available: http//psych.upenn.edu/backuslab/helmholtz

[62] R. M. Burde and S. E. Feldon, "The extraocular muscles," in *Adler's Physiology of the Eye*. St. Louis, MO, USA: Mosby, 1981, pp. 84–121.

[63] L. Apt, "An anatomical reevaluation of rectus muscle insertions," *Trans. Amer. Ophthalmol. Soc.*, vol. 78, pp. 365–375, Jun. 1980.

[64] R. G. Scobee, *The Oculorotary Muscles*. St. Louis, MO, USA: Mosby, 1952.

[65] R. A. Clark, J. M. Miller, and J. L. Demer, "Three-dimensional location of human rectus pulleys by path inflections in secondary gaze positions," *Invest. Ophthalmol. Vis. Sci.*, vol. 41, no. 12, pp. 3787–3797, 2000.

[66] F. C. Donders, "Contribution to the teaching of the movements of the human eye," *Holland Beitr Anat Physiol. Wiss*, vol. 1, no. 104, p. 384, 1848.

[67] H. Von Helmholtz, *Handbuch der Physiologischen Optik*, vol. 9. Richardson, TX, USA: Voss, 1867.

[68] A. M. F. Wong, "Listing's law: Clinical significance and implications for neural control," *Survey Ophthalmol.*, vol. 49, no. 6, pp. 563–575, 2004.

[69] A. M. F. Wong, J. A. Sharpe, and D. Tweed, "Adaptive neural mechanism for listing's law revealed in patients with fourth nerve palsy," *Invest. Ophthalmol. Vis. Sci.*, vol. 43, no. 6, pp. 1796–1803, 2002.

[70] D. A. Robinson, "A method of measuring eye movemnent using a scieral search coil in a magnetic field," *IEEE Trans. Bio-Med. Eng.*, vol. 10, no. 4, pp. 137–145, Oct. 1963.

[71] D. A. Robinson, "A quantitative analysis of extraocular muscle cooperation and squint," *Invest. Ophthalmol. Vis. Sci.*, vol. 14, no. 11, pp. 801–825, 1975.

[72] J. D. Crawford and E. M. Klier, "Neural control of three-dimensional gaze shifts," in *The Oxford Handbook of Eye Movements*. London, U.K.: Oxford Univ. Press, 2011, p. 339, doi: 10.1093/oxfordhb/9780199539789.013.0018.

[73] T. Haslwanter, "Mathematics of three-dimensional eye rotations," *Vis. Res.*, vol. 35, no. 12, pp. 1727–1739, 1995.

[74] T. Haslwanter, "Mechanics of eye movements: Implications of the 'orbital revolution,'" *Ann. New York Acad. Sci.*, vol. 956, no. 1, pp. 33–41, 2002.

[75] G. Westheimer, "Kinematics of the eye," *J. Opt. Soc. Amer.*, vol. 47, no. 10, pp. 967–974, 1957.

[76] J. D. Crawford, J. C. Martinez-Trujillo, and E. M. Klier, "Neural control of three-dimensional eye and head movements," *Current Opinion Neurobiol.*, vol. 13, no. 6, pp. 655–662, 2003.

[77] D. Tweed, W. Cadera, and T. Vilis, "Computing three-dimensional eye position quaternions and eye velocity from search coil signals," *Vis. Res.*, vol. 30, no. 1, pp. 97–110, 1990.

[78] L. Ferman, H. Collewijn, and A. V. Van den Berg, "A direct test of Listing's law—I. Human ocular torsion measured in static tertiary positions," *Vis. Res.*, vol. 27, no. 6, pp. 929–938, 1987.

[79] L. Ferman, H. Collewijn, and A. V. Van den Berg, "A direct test of Listing's law—II. Human ocular torsion measured under dynamic conditions," *Vis. Res*, vol. 27, no. 6, pp. 939–951, 1987.

[80] M. F. Walker, M. Shelhamer, and D. S. Zee, "Eye-position dependence of torsional velocity during interaural translation, horizontal pursuit, and yaw-axis rotation in humans," *Vis. Res.*, vol. 44, no. 6, pp. 613–620, 2004.

[81] H. Misslisch, D. Tweed, M. Fetter, D. Sievering, and E. Koenig, "Rotational kinematics of the human vestibuloocular reflex. III. Listing's law," *J. Neurophysiol.*, vol. 72, no. 5, pp. 2490–2502, 1994.

[82] L. Ferman, H. Collewijn, T. C. Jansen, and A. V. Van den Berg, "Human gaze stability in the horizontal, vertical and torsional direction during voluntary head movements, evaluated with a three-dimensional scleral induction coil technique," *Vis. Res.*, vol. 27, no. 5, pp. 811–828, 1987.

[83] A. W. Volkmann, "On the mechanics of the eye muscles," *Ber. Verh. K. Saechs. Ges. Wiss.*, vol. 21, p. 28, 1869.

[84] Z. Gao, H. Guo, and W. Chen, "Initial tension of the human extraocular muscles in the primary eye position," *J. Theor. Biol.*, vol. 353, pp. 78–83, Jul. 2014.

[85] H. Guo, Z. Gao, and W. Chen, "Contractile force of human extraocular muscle: A theoretical analysis," *Appl. Bionics Biomech.*, vol. 2016, Mar. 2016, Art. no. 4091824.

[86] Q. Wei, S. Sueda, and D. K. Pai, "Biomechanical simulation of human eye movement," in *Proc. Int. Symp. Biomed. Simulation*, 2010, pp. 108–118.

[87] J. L. Demer and J. M. Miller, "Magnetic resonance imaging of the functional anatomy of the superior oblique muscle," *Invest. Ophthalmol. Vis. Sci.*, vol. 36, no. 5, pp. 906–913, 1995.

[88] R. Kono, V. Poukens, and J. L. Demer, "Superior oblique muscle layers in monkeys and humans," *Invest. Ophthalmol. Vis. Sci.*, vol. 46, no. 8, pp. 2790–2799, 2005.

[89] D. A. Robinson, D. M. O'Meara, A. B. Scott, and C. C. Collins, "Mechanical components of human eye movements," *J. Appl. Physiol.*, vol. 26, no. 5, pp. 548–553, 1969.

[90] C. C. Collins, A. B. Scott, and D. M. O'Meara, "Elements of the peripheral oculomotor aparatus," *Optometry Vis. Sci.*, vol. 46, no. 7, pp. 510–515, 1969.

[91] C. C. Collins, "Orbital mechanics," in *The Control of Eye Movements*. San Diego, CA, USA: Academic, 1971, pp. 283–325. [Online]. Available: https://doi.org/10.1016/B978-0-12-071050-8.50015-X

[92] C. C. Collins, D. O'Meara, and A. B. Scott, "Muscle tension during unrestrained human eye movements," *J. Physiol.*, vol. 245, no. 2, pp. 351–369, 1975.

[93] G. Lennerstrand, R. Bolzani, M. Benassi, S. Tian, and C. Schiavi, "Isometric force development in human horizontal eye muscles and pulleys during saccadic eye movements," *Acta Ophthalmol.*, vol. 87, no. 8, pp. 837–842, 2009.

[94] G. Lennerstrand, C. Schiavi, S. Tian, M. Benassi, and E. C. Campos, "Isometric force measured in human horizontal eye muscles attached to or detached from the globe," *Graefe's Arch. Clin. Experim. Ophthalmol.*, vol. 244, no. 5, pp. 539–544, 2006.

[95] C. C. Collins, M. R. Carlson, A. B. Scott, and A. Jampolsky, "Extraocular muscle forces in normal human subjects," *Invest. Ophthalmol. Vis. Sci.*, vol. 20, no. 5, pp. 652–664, 1981.

[96] R. Kono, R. A. Clark, and J. L. Demer, "Active pulleys: Magnetic resonance imaging of rectus muscle paths in tertiary gazes," *Invest. Ophthalmol. Vis. Sci.*, vol. 43, no. 7, pp. 2179–2188, 2002.

[97] J. L. Demer, S. Y. Oh, and V. Poukens, "Evidence for active control of rectus extraocular muscle pulleys," *Invest. Ophthalmol. Vis. Sci.*, vol. 41, no. 6, pp. 1280–1290, 2000.

[98] A. F. Fuchs and M. D. Binder, "Fatigue resistance of human extraocular muscles," *J. Neurophysiol.*, vol. 49, no. 1, pp. 28–34, 1983.

[99] J. D. Porter, R. S. Baker, R. J. Ragusa, and J. K. Brueckner, "Extraocular muscles: Basic and clinical aspects of structure and function," *Survey Ophthalmol.*, vol. 39, no. 6, pp. 451–484, 1995.

[100] A. B. Scott and C. C. Collins, "Division of labor in human extraocular muscle," *Arch. Ophthalmol.*, vol. 90, no. 4, pp. 319–322, 1973.

[101] L. D. Peachey and A. F. Huxley, "Structural identification of twitch and slow striated muscle fibers of the frog," *J. Cell Biol.*, vol. 13, no. 1, pp. 177–180, 1962.

[102] E. Henneman and C. B. Olson, "Relations between structure and function in the design of skeletal muscles," *J. Neurophysiol.*, vol. 28, no. 3, pp. 581–598, 1965.

[103] J. M. Miller, "Understanding and misunderstanding extraocular muscle pulleys," *J. Vis.*, vol. 7, no. 11, p. 10, 2007.

[104] P. Boeder, "Co-operative action of extra-ocular muscles," *Brit. J. Ophthalmol.*, vol. 46, no. 7, pp. 397–403, 1962.

[105] W. E. Krewson, III, "The action of the extraocular muscles: A method of vector-analysis with computations," *Trans. Amer. Ophthalmol. Soc.*, vol. 48, pp. 443–486, Feb. 1950.

[106] J. M. Miller, "Functional anatomy of normal human rectus muscles," *Vis. Res.*, vol. 29, no. 2, pp. 223–240, 1989.

[107] J. M. Miller, J. L. Demer, and A. L. Rosenbaum, "Effect of transposition surgery on rectus muscle paths by magnetic resonance imaging," *Ophthalmology*, vol. 100, no. 4, pp. 475–487, 1993.

[108] R. A. Clark, J. M. Miller, and J. L. Demer, "Location and stability of rectus muscle pulleys. Muscle paths as a function of gaze," *Invest. Ophthalmol. Vis. Sci.*, vol. 38, no. 1, pp. 227–240, 1997.

[109] J. M. Miller, I. Shamaeva, and D. S. Pavlovski, *Orbit 1.5 Gaze Mechanics Simulation*. San Francisco, CA, USA: Eidactics, 1995.

[110] J. M. Miller, D. S. Pavlovski, and I. Shaemeva, *Orbit 1.8 Gaze Mechanics Simulation*. San Francisco, CA, USA: Eidactics, 1999. [Online]. Available: http://www.eidactics.com/projects/ooi

[111] M. Buchberger, "Biomechanical modelling of the human eye," Ph.D. dissertation, Johannes Kepler Univ. Linz, Linz, Austria, 2004.

[112] T. Haslwanter, M. Buchberger, T. Kaltofen, R. Hoerantner, and S. Priglinger, "SEE++: A biomechanical model of the oculomotor plant," *Annu. New York Acad. Sci.*, vol. 1039, no. 1, pp. 9–14, 2005.

[113] R. F. Spencer and J. D. Porter, "Structural organization of the extraocular muscles," *Rev. Oculomotor Res.*, vol. 2, pp. 33–79, Jan. 1987.

[114] M. J. Stokes, R. G. Cooper, and R. H. Edwards, "Normal muscle strength and fatigability in patients with effort syndromes," *Brit. Med. J.*, vol. 297, no. 6655, pp. 1014–1017, 1988.

[115] N. K. Vøllestad, "Measurement of human muscle fatigue," *J. Neurosci. Methods*, vol. 74, no. 2, pp. 219–227, 1997.

[116] J. DeLuca, *Fatigue as a Window to the Brain*. Cambridge, MA, USA: MIT Press, 2005.

[117] D. E. Broadbent, *Decision and Stress*. San Francisco, CA, USA: Academic, 1971.

[118] W. Muncie, "Chronic fatigue," *Psychosomatic Med.*, vol. 3, no. 3, pp. 277–285, 1941.

[119] S. Wessely, M. Sharpe, and M. Hotopf, *Chronic Fatigue and its Syndromes*. London, U.K.: Oxford Univ. Press, 1998.

[120] E. Jackson, "Visual fatigue," *Amer. J. Ophthalmol.*, vol. 4, no. 2, pp. 119–122, 1921.

[121] D. Schmidt, L. A. Abel, L. F. DellOsso, and R. B. Daroff, "Saccadic velocity characteristics- intrinsic variability and fatigue," *Aviation, Space, Environ. Med.*, vol. 50, no. 4, pp. 393–395, 1979.

[122] S. Saito, "Does fatigue exist in a quantitative measurement of eye movements?" *Ergonomics*, vol. 35, nos. 5–6, pp. 607–615, 1992.

[123] J. Kuze and K. Ukai, "Subjective evaluation of visual fatigue caused by motion images," *Displays*, vol. 29, no. 2, pp. 159–166, 2008.

[124] M. Ogata, K. Ukai, and T. Kawai, "Visual fatigue in congenital nystagmus caused by viewing images of color sequential projectors," *J. Display Technol.*, vol. 1, no. 2, p. 314, 2005.

[125] K. Brunnström, K. Wang, S. Tavakoli, and B. Andrén, "Symptoms analysis of 3D TV viewing based on Simulator Sickness Questionnaires," *Quality User Exper.*, vol. 2, no. 1, p. 1, 2017.

[126] S. Ohno and K. Ukai, "Subjective evaluation of motion sickness following game play with head mounted display," *J. Inst. Image Inf. Television Engineers*, vol. 54, no. 6, pp. 887–891, 2000.

[127] A. T. Bahill and L. Stark, "Overlapping saccades and glissades are produced by fatigue in the saccadic eye movement system," *Experim. Neurol.*, vol. 48, no. 1, pp. 95–106, 1975.

[128] A. T. Bahill and B. T. Troost, "Types of saccadic eye movements," *Neurology*, vol. 29, no. 8, pp. 1150–1152, 1979.

[129] S. Mun, M.-C. Park, S. Park, and M. Whang, "SSVEP and ERP measurement of cognitive fatigue caused by stereoscopic 3D," *Neurosci. Lett.*, vol. 525, no. 2, pp. 89–94, 2012.

[130] J. Coyne and C. Sibley, "Investigating the use of two low cost eye tracking systems for detecting pupillary response to changes in mental workload," *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 60, no. 1, pp. 37–41, 2016.

[131] S. Zugal and J. Pinggera, "Low–cost eye–trackers: Useful for information systems research?" in *Proc. Int. Conf. Adv. Inf. Syst. Eng.*, 2014, pp. 159–170.

[132] V. Janthanasub and P. Meesad, "Evaluation of a low-cost eye tracking system for computer input," *Int. J. Appl. Sci. Technol.*, vol. 8, no. 3, pp. 185–196, 2015.

[133] Q. Ji and X. Yang, "Real-time eye, gaze, and face pose tracking for monitoring driver vigilance," *Real-Time Imag.*, vol. 8, no. 5, pp. 357–377, 2002.

[134] Q. Ji, Z. Zhu, and P. Lan, "Real-time nonintrusive monitoring and prediction of driver fatigue," *IEEE Trans. Veh. Technol.*, vol. 53, no. 4, pp. 1052–1068, Jul. 2004.

[135] W.-B. Horng, C.-Y. Chen, Y. Chang, and C.-H. Fan, "Driver fatigue detection based on eye tracking and dynamk, template matching," in *Proc. IEEE Int. Conf. Netw., Sens. Control*, vol. 1. Mar. 2004, pp. 7–12.

[136] M. Eriksson and N. P. Papanikotopoulos, "Eye-tracking for detection of driver fatigue," in *Proc. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Nov. 1997, pp. 314–319.

[137] Z. Zhang and J. Zhang, "A new real-time eye tracking for driver fatigue detection," in *Proc. 6th Int. Conf. ITS Telecommun.*, 2006, pp. 8–11.

[138] Q. Wang, J. Yang, M. Ren, and Y. Zheng, "Driver fatigue detection: A survey," in *Proc. 6th World Congr. Intell. Control Autom. (WCICA)*, vol. 2. Jun. 2006, pp. 8587–8591.

[139] P.-A. Blanche, "Toward the ultimate 3-D display," *Inf. Display*, vol. 28, nos. 2–3, pp. 32–37, 2012.

[140] G. Kramida, "Resolving the vergence-accommodation conflict in head-mounted displays," *IEEE Trans. Vis. Comput. Graphics*, vol. 22, no. 7, pp. 1912–1931, Jul. 2016.
[141] T. Bando, A. Iijima, and S. Yano, "Visual fatigue caused by stereoscopic images and the search for the requirement to prevent them: A review," *Displays*, vol. 33, no. 2, pp. 76–83, 2012.
[142] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks, "Vergence–accommodation conflicts hinder visual performance and cause visual fatigue," *J. Vis.*, vol. 8, no. 3, p. 33, 2008.
[143] F. Toates, "Accommodation function of the human eye," *Physiol. Rev.*, vol. 52, no. 4, pp. 828–863, 1972.
[144] E. F. Fincham and J. Walton, "The reciprocal actions of accommodation and convergence," *J. Physiol.*, vol. 137, no. 3, pp. 488–508, 1957.
[145] M. Lambooij, M. Fortuin, I. Heynderickx, and W. IJsselsteijn, "Visual discomfort and visual fatigue of stereoscopic displays: A review," *J. Imag. Sci. Technol.*, vol. 53, no. 3, pp. 30201-1–30201-14, 2009.
[146] K. Tung, M. Miller, J. Colombi, D. Uribe, and S. Smith, "Effect of vibration on eye, head and helmet movements while wearing a helmet-mounted display," *J. Soc. Inf. Display*, vol. 22, no. 10, pp. 535–544, 2014.
[147] G. Nicholson, "Head-mounted display (HMD) assessment for tracked vehicles," *Proc. SPIE*, vol. 8042, p. 80420I, Jun. 2011.
[148] C. Rash, W. McLean, B. Mozo, J. Licina, and B. McEntire, "Human factors and performance concerns for the design of helmet-mounted displays," in *Proc. RTO HFM Symp. Current Aeromed. Issues Rotary Wing Oper.*, 1999, pp. 1–331.
[149] M. J. Griffin and C. H. Lewis, "A review of the effects of vibration on visual acuity and continuous manual control, part I: Visual acuity," *J. Sound Vibrat.*, vol. 56, no. 3, pp. 383–413, 1978.
[150] M. J. Griffin, *Handbook of Human Vibration*. San Francisco, CA, USA: Academic, 2012.
[151] F. Seagull and C. Wickens, "Vibration in command and control vehicles: Visual performance, manual performance, and motion sickness: A review of the literature," Hum. Factors Division, Inst. Aviation, Univ. Illinois Urbana–Champaign, Champaign, IL, USA, Tech. Rep., 2006.
[152] A. Nakashima and B. Cheung, "The effects of vibration frequencies on physical, perceptual and cognitive performance," Defence Res. Develop., Toronto, ON, Canada, Tech. Rep. TR 2006-218, 2006.
[153] J. O. Brooks *et al.*, "Simulator sickness during driving simulation studies," *Accident Anal. Prevention*, vol. 42, no. 3, pp. 788–796, 2010.
[154] S. Nahavandi, Z. Najdovski, B. Horan, and A. Bhatti, "Universal motion simulator," U.S. Patent 0 096 276 A1, Apr. 7, 2015,
[155] H. Asadi, A. Mohammadi, S. Mohamed, and S. Nahavandi, "Adaptive translational cueing motion algorithm using fuzzy based tilt coordination," in *Proc. Int. Conf. Neural Inf. Process.*, 2014, pp. 474–482.
[156] H. Asadi, S. Mohamed, D. R. Zadeh, and S. Nahavandi, "Optimisation of nonlinear motion cueing algorithm based on genetic algorithm," *Veh. Syst. Dyn.*, vol. 53, no. 4, pp. 526–545, 2015.
[157] H. Asadi, S. Mohamed, C. P. Lim, and S. Nahavandi, "Robust optimal motion cueing algorithm based on the linear quadratic regulator method and a genetic algorithm," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 2, pp. 238–254, Feb. 2017.
[158] H. Teufel *et al.*, "MPI motion simulator: Development and analysis of a novel motion simulator," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, 2007, pp. 1–11.
[159] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *Int. J. Aviation Psychol.*, vol. 3, no. 3, pp. 203–220, 1993.
[160] E. F. Miller, II, and A. Graybiel, *Comparison of Five Levels of Motion Sickness Severity as the Basis for Grading Susceptibility*, document ID 19740051130, Aerospace Medicine, USA, Jun. 1974, pp. 602–603.
[161] R. S. Kellogg, R. S. Kennedy, and A. Graybiel, "Motion sickness symptomatology of labyrinthine defective and normal subjects during zero gravity maneuvers," Aerospace Med. Res. Labs, Wright-Patterson, OH, USA, Tech. Rep. AMRL-TDR-64-47, AD-603339, 1964.
[162] B. D. Lawson, "Motion sickness symptomatology and origins," in *Handbook of Virtual Environments: Design, Implementation, and Applications*, K. S. Hale and K. M. Stanney, Eds. Boca Raton, FL, USA: CRC Press, 2014, pp. 532–587.
[163] K. M. Stanney and R. S. Kennedy, "The psychometrics of cybersickness," *Commun. ACM*, vol. 40, no. 8, pp. 66–68, 1997.
[164] J. Lackner and P. DiZio, "Gravitational, inertial, and coriolis force influences on nystagmus, motion sickness, and perceived head trajectory," in *The Head-Neck Sensory Motor System*. New York, NY, USA: Oxford Univ. Press, 1992, pp. 216–222.
[165] G. Bertolini and D. Straumann, "Moving in a moving world: A review on vestibular motion sickness," *Frontiers Neurol.*, vol. 7, p. 14, Feb. 2016.
[166] M. Hossny, D. Nahavandi, S. Nahavandi, V. Haydari, and S. Harding, "Musculoskeletal analysis of mining activities," in *Proc. IEEE Int. Symp. Syst. Eng. (ISSE)*, Sep. 2015, pp. 184–189.
[167] M. S. DeMers, J. L. Hicks, and S. L. Delp, "Preparatory co-activation of the ankle muscles may prevent ankle inversion injuries," *J. Biomech.*, vol. 52, pp. 17–23, Feb. 2017.
[168] J. T. Ji, R. H. So, and R. T. Cheung, "Isolating the effects of vection and optokinetic nystagmus on optokinetic rotation-induced motion sickness," *Hum. Factors*, vol. 51, no. 5, pp. 739–751, 2009.
[169] H. Guo, Z. Gao, and W. Chen, "The biomechanical significance of pulley on binocular vision," *Biomed. Eng. OnLine*, vol. 15, no. 2, p. 507, 2016.
[170] P. Pascolo and R. Carniel, "From time series analysis to a biomechanical multibody model of the human eye," *Chaos, Solitons Fractals*, vol. 40, no. 2, pp. 966–974, 2009.
[171] Q. Wei, S. Sueda, and D. K. Pai, "Physically-based modeling and simulation of extraocular muscles," *Progr. Biophys. Molecular Biol.*, vol. 103, no. 2, pp. 273–283, 2010.
[172] N. Hansen, "The CMA evolution strategy: A comparing review," in *Towards a New Evolutionary Computation*. Berlin, Germany: Springer, 2006, pp. 75–102.
[173] A. N. Vasavada, S. Li, and S. L. Delp, "Influence of muscle morphometry and moment arms on the moment-generating capacity of human neck muscles," *Spine*, vol. 23, no. 4, pp. 412–422, 1998.
[174] D. Straumann, D. S. Zee, D. Solomon, and P. Kramer, "Validity of Listing's law during fixations, saccades, smooth pursuit eye movements, and blinks," *Experim. Brain Res.*, vol. 112, no. 1, pp. 135–146, 1996.
[175] J. L. Hicks, T. K. Uchida, A. Seth, A. Rajagopal, and S. L. Delp, "Is my model good enough? Best practices for verification and validation of musculoskeletal models and simulations of movement," *J. Biomech. Eng.*, vol. 137, no. 2, p. 020905, 2015.
[176] K. P. Weber, S. M. Rosengren, R. Michels, V. Sturm, D. Straumann, and K. Landau, "Single motor unit activity in human extraocular muscles during the vestibulo-ocular reflex," *J. Physiol.*, vol. 590, no. 13, pp. 3091–3101, 2012.
[177] I. Strachan and B. Brown, "Electromyography of extraocular muscles in Duane's syndrome," *Brit. J. Ophthalmol.*, vol. 56, no. 8, p. 594, 1972.
[178] N. Galldiks and W. F. Haupt, "Diagnostic value of the electromyography of the extraocular muscles," *Clin. Neurophysiol.*, vol. 119, no. 12, pp. 2785–2788, 2008.
[179] R. D. Crowninshield, "Use of optimization techniques to predict muscle forces," *J. Biomech.*, vol. 12, no. 8, p. 627, 1979.
[180] R. D. Crowninshield and R. A. Brand, "A physiologically based criterion of muscle force prediction in locomotion," *J. Biomech.*, vol. 14, no. 11, pp. 793–801, 1981.
[181] A. Seth, M. Sherman, J. A. Reinbolt, and S. L. Delp, "OpenSim: A musculoskeletal modeling and simulation framework for *in silico* investigations and exchange," *Procedia IUTAM*, vol. 2, pp. 212–232, Jan. 2011.
[182] D. G. Thelen and F. C. Anderson, "Using computed muscle control to generate forward dynamic simulations of human walking from experimental data," *J. Biomech.*, vol. 39, no. 6, pp. 1107–1115, 2006.
[183] D. G. Thelen, F. C. Anderson, and S. L. Delp, "Generating dynamic simulations of movement using computed muscle control," *J. Biomech.*, vol. 36, no. 3, pp. 321–328, 2003.
[184] T. S. Buchanan, D. G. Lloyd, K. Manal, and T. F. Besier, "Estimation of muscle forces and joint moments using a forward-inverse dynamics model," *Med. Sci. Sports Exercise*, vol. 37, no. 11, pp. 1911–1916, 2005.

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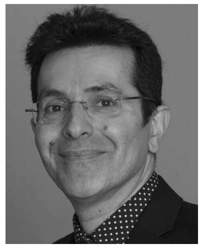

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