IMPERIAL

Designing an active surrogate neck for brain injury research for heading in football

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Abstract

Heading is a common occurrence in football games and appears to cause degradation of brain cells as well as show an increased risk of developing neurodegenerative diseases in later life. To reduce the damage one approach is looking at redesigning the footballs, to do this a method needs to be devised to provide a fair comparison between balls. Surrogate neck models can be used to accurately quantify the impact and damage, used extensively through brain injury research and industry. They are most commonly used in automotive testing where they provide a reliable and repeatable way to compare impacts. Current mechanical surrogate neck models are often designed around maintaining a fixed head position focusing on the movement in a single fixed plane and have higher resistance to motion, beyond physiological norms. This project aims to begin work on developing a surrogate neck which will actively move to header a ball to, as close as possible, approximate the motion and resistance of a human neck during a football game.

Declaration of Originality

I hereby declare that the work presented in this thesis is my own unless otherwise stated. To the best of my knowledge the work is original and ideas developed in collaboration with others have been appropriately referenced.

Copyright Declaration

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List of Acronyms

TBIs Traumatic Brain Injuries

ATDs Anthropomorphic test devices

H3SN Hybrid III surrogate neck

THOR Test device for Human Occupant Restraint

THOR-M Test device for Human Occupant Restraint - Modified

1 Introduction

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1.1 Introduction

Football is the most popular sport with over 128,000 professionals (FIFA 2023) and 265 million players world wide (TAHA et al. 2015). Whilst it has been proven to have significant health benefits (Krustrup 2018; Milanović et al. 2019), players can often occur injuries during play around 22% of which are head injuries (Tracey Covassin and Sachs 2003). Purposeful heading of the football is an intrinsic part of the sport with each player heading the ball between six and twelve times per game (Levy et al. 2012; Spiotta et al. 2012). Whilst this may seem an insignificant number one study found that 46% of players had experienced the symptoms of a concussion within the past season, with 75% of those experiencing a reoccurrence and 70% of those not recognising the symptoms (Delaney et al. 2001). This level of repetative damage has been proposed as a contributing factor to the increased prevalence of neurodegenerative diseases observed among former professional players (Mackay et al. 2019; RUSSELL et al. 2021; Ueda et al. 2023; Orhant et al. 2022). Systematic reviews assessing the acute effects of heading in football generally indicate no statistically significant overall impact across studies. but, recognize that certain individual studies report transient, deleterious neurological outcomes, suggesting the potential for short-term adverse effects under specific conditions(Tarnutzer et al. 2017; Kontos et al. 2016; McCunn et al. 2021).

This research has lead many major governing bodies in football, such as the premier league to want to adapt the game in order to protect their players better. By adapting the design of their footballs they hope to reduce the impact and potential for injury when heading. To do this a standarised way of comparing the footballs is required. In other sports such as cycling and American football surrogate models are used to test helmets and to understand the rotational and linear kinematics which the athletes experience (Baker et al. 2024; A 2013), enabling a more accurate understanding of the damaged caused. Having an accurate neck response to impact is important as neck strength has been shown to reduce head acceleration and impact during purposeful headering(Peek et al. 2020) as well as head impacts during other sports (Collins et al. 2014; Nutt et al. 2022; Farmer et al. 2020).

1.1.1 Surrogate Models

Surrogates are widely used as they allow for tests to be standardised, reproduced and for the response to be as biofidelic as possible. They are desirable as they allow researchers to accurately determine how a human would respond to an impact with out endangering a living human (Crandall et al. 2011). Surrogate necks have been highly praised by experts in their ability to improve understanding head impacts (Funk et al. 2022)

1.1.2 Innovation

The innovation proposed in this project specifically targets the movement the head makes before contact with the ball in a heading maneuver and how this affects the impact on the brain after. The project aims to begin work on developing a surrogate neck model that is dynamically active, capable of self movement whilst maintaining the flex of an active neck, enabling a more accurate representation of what football players experience.

The project will achieve this by using computational modeling in MADYMO(Andrew Post and Gilchrist 2014) to gain an understanding in the relevant neck muscles used, and research from past experiments, particularly ones with human trials to validate data collected. The final outcome will be accurate data with which a new design for a surrogate neck can be designed specifically for football.

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2.1 Current State of the Art

There are currently a few different surrogate head and neck models available for testing, each designed for different metrics, but mainly focused around automotive crash tests. In sports impact testing it is common practice to use no surrogate neck at all to reduce the impact of bias, such as those done for cycle helmet testing where the European standard is to use a fixed head(E. S. Walsh et al. 2018). This is a cause for concern as this restricts the impact analysis to purely linear translation, where as rotational head motion has shown to lead to concussive brain injury (King et al. 2003; Forero Rueda et al. 2011; Post and Blaine Hoshizaki 2015).

2.1.1 Current necks available

Test device for Human Occupant Restraint - Modified (THOR-M) (Ridella and Parent 2011): Widely considered to be the best for automotive crash testing(Farmer et al. 2022). It is an advancement on the Test device for Human Occupant Restraint (THOR) platform, with the ability to move in all three anatomical planes and have both active and passive neck musculature stiffness properties. It doesn't fully align with computational models, such as the Duke Adult Head and Neck Model(DAHNM) being an order of magnitude stiffer in axial rotation response (Luck et al. 2014; Farmer et al. 2022).

Hybrid III surrogate neck (H3SN) (Foster et al. 1977): Designed for frontal collisions it is the most widely used and well documented model to date often used for sports applications such as Ameriacn football(Post, Oeur, E. Walsh, et al. 2014) and ice hockey(Post, Oeur, Hoshizaki, et al. 2013) Originally the ATD 502, developed in 1973 by General Motors(Hubbard 1975), it has been iterated upon to increase its biofidelity. However, it is often criticised for having a much higher stiffness for axial compression which it wasn't designed for(Sances Jr and Kumaresan 2001; Nordhoff et al. 2007).

Unbiased neck design (E. S. Walsh et al. 2018): Based on the neck design of the H3SN it matched the same mass and dimensions, but was designed to have consistent deflections for front, side and rear impacts. However, it did not assess the bio-fidelity of the design and there were no other papers found testing this model. The aim of the design was to remove the mechanical bias provided by the H3SN, not to provide or validate a neck test device that would respond in the same way as a human neck would under impact.

New surrogate neck design (MacGillivray et al. 2021): Designed to improve accuracy of a surrogate neck for American football helmet collisions, it showed improvement over the H3SN model for it's particular application demonstrating that through designing for specific applications advancements could be made. It still operated as a purely resistive neck with no capacity to move on it's own.

2.2 Gap in the Knowledge base

The analysis revealed that most surrogate necks have been designed for automotive crash tests and have such been designed in a simplified and more resilient way that ensures reproducibility and durability ensuring they don't break or loose their properties during high-speed collisions. Often they have been simplified to act in one plane such as the H3SN(Foster et al. 1977), BioRID(Linder et al. 2002) and World-SID(D et al. 2001) necks which have been developed specifically for frontal, rear and near-side collisions respectfully(Farmer et al. 2022). The validation of their metrics also comes through torso loading scenarios, not the direct head impact which a football would cause, reducing the accuracy of the results. So, while they appear to be biofidelic for their specialised application there is some debate to be had on how well they work for other types of impacts. Additionally, compared to most areas where head impacts occur football has a unique aspect in which the player is actively trying to cause the impact creating the need for study into new surrogate neck designs. This gap reduces the accuracy of the data available for the true implications and injuries sustained during football.

The analysis also showed no evidence of any computational simulation for mobile neck motion, to actively header a football, with all current research focusing on a fixed head and often no neck at all.

2.3 Conclusion of Literature Review

The current state of the art demonstrates that there is currently no surrogate neck model which has been designed to deal with the complex motion that is involved in heading. Whilst the designs of necks such as the H3SN and THOR-M are widely used for many different areas of research, they have been shown to be biofidelic for only the specific impacts they were designed for (car crashes), and having much higher resistance for other impacts. With research showing how increased neck strength can alter the impact and damage to the brain caused, it poses the question how reliable is the data collected for other types of impacts? Another conclusion was that none of the commonly used neck models could independently move, one of the more unique aspects of football headering is the intentional head movement towards the impact giving the neck having different levels of extension when doing so. This lack of specific neck model and computational motion analysis showed the need for development. The proposed project aims to address these issues by building a platform to develop a more biofidelic surrogate neck.

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Project Overview

3.1 Project Objectives and Scope

3.1.1 Objectives

With the ultimate objective set on a biofidelic neck which is fully responsive and able to preform a number of different heading motions to allow for a better understanding of how to redesign footballs to make them safer. This project recognises its constraints on time and budget. Therefore, for this project, the primary objectives are:

- **Develop an understanding of the neck muscles and bones involved in a heading movement**: To determine which ones play an active role and the forces they experience in order to start constructing a new surrogate neck model.
- **Run simulations of heading maneuvers**: Using MADYMO to animate the head and identify forces and stresses required for each area, as well as looking at how different heading styles effect the results.
- **Analyse heading style**: Using the simulations analyse the difference between defensive and attacking headers.

3.1.2 Scope

The scope of the project includes:

- **Neck muscle engagement understanding**: Using MADYMO modeling to understand how neck muscle activation can move the head.
- **Data collection on required parameters**: Simulating heading motion to calculate the joints and movement of the head.
- **Heading comparison**: Looking at how the impact changes based on how the head is positioned before impact.
- **Out of Scope**: Designing the neck is not within the scope of this project.

3.1.3 Next Steps

Once the initial parameters of the head-form have been characterised they will be used to inform design of the new neck model.

- **Design a concept within CAD**: Design an initial concept within the virtual environment that is able to move on it's own, following the motion and speed of a header in a professional game. Along with the ability to compress and respond to an impact from a football in as similar as possible way to a human.
- **Minimise components**: reduce system complexity to improve the system reliability, reproducibility and reduce chance of failure. All key metrics as seen from the literature review allowing for more confidence in results.
- **Validate the concept**: Run simulations to test the concept in the virtual environment and use prototypes to validate mechanism designs.
- **Build and validate working model**: Once each element has been tested a complete model will need to be built and validated.

3.2 Proposed Methodology

3.2.1 Background understanding

To insure a well informed design process, a comprehensive review of the best performing surrogate models will be done to look at the different techniques to achieve biofidelity.

1. **Literature review**: Analyzing existing studies on surrogate necks used in biomechanical research as well as advancements in Anthropomorphic test devices (ATDs) focusing on neck motion, active muscle simulation, and biofidelity.
2. **Assessment of current models**: Identifying strengths, limitations, and gaps in the motion capabilities of existing surrogate necks, specifically looking at football heading.
3. **Secondary data collection**: Collecting information on accelerations, forces and other data collected by different studies with which to compare results. Gathering data from simulations, surrogate tests and live participant studies.
4. **Football data collection**: Finding data on the properties of commonly used footballs, looking at usual impact speeds, rotation and angle. As well as how the players header the ball, looking at attacking and defencive styles.
5. **Standards and guidelines**: Reviewing biomechanical standards for surrogate systems to ensure compliance with established protocols.

3.2.2 Setup and Simulations

1. **Model setup**:
    - A virtual simulation environment will be created in MADYMO (Mathematical Dynamic Models), leveraging its capabilities for multibody dynamics and finite element analysis.
    - An anatomically accurate model of the human neck, including vertebrae, intervertebral discs, and key muscle groups, will be used. Involving active muscle components and joints for dynamics.
2. **Simulation Scenarios**:

- Simulations will replicate dynamic conditions of heading a football, focusing on forces, accelerations, and angular displacements.
- Iterative tests will be performed to assess the interaction between muscle forces and joint motion.
- Scenarios will include simulations where the head remains stationary as well as actively moving towards the ball as well as headers performed at different speeds, both of the ball and the head.

3. **Analyse data**:
   - Comparison of collected data to those found by other research papers.
   - Key metrics may include: Neck range of motion, muscle activation, linear and rotational accelerations.
4. **Design requirement identification**:
   - Insights from MADYMO simulations will inform the structural and functional design of the surrogate neck.
   - Parameters such as necessary degrees of freedom, load-bearing capacity, and muscle analogs will be extracted to ensure biofidelity.

3.2.3 Validation

Validation will be based on studying metrics collected from prior research such as data from live participants, other surrogate models and other computational analysis. Along with qualitative data from video footage.

3.3 Wider Context and Industry Impact

Developing a highly accurate surrogate head for testing impacts during heading has significant implications for the game. By providing a tool which provides accurate, reliable and reproducible results to analyse the impact caused by a ball will enable a greater understanding of how adaptations to the design of the ball can better protect players from the immediate problem of concussions or Traumatic Brain Injuries (TBIs) to longer term effects such as developing neurodegenerative diseases and increased mortality.

3.4 Wider Context Figure:

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Figure 3.1: Wider Context

Conclusions

This project aims to address the limitations in current surrogate neck design when used for the analysis of headering in football. It will focus on increasing biofidelity through simulating the head motion that a player performs during a heading maneuver, to understand the required properties of the neck muscles and bones involved.

The successful completion of the project will contribute to the field by:

- Further demonstrating the requirement for a new neck form design to analyse heading in football.
- Starting the development of a platform which can be used to accurately compare the designs of different footballs in order to inform future design to reduce the head injury caused through impact.
- Providing a foundation for future design into sport-specific surrogate models for more accurate testing.

This is in alignment with the wider context of understanding and reducing the impact of headering in football.

Bibliography

A, MacAlister (Apr. 2013). "Surrogate Head Forms for the Evaluation of Head Injury Risk." In: *Brain Injuries and Biomechanics Symposium*. DOI: http://hdl.handle.net/10919/23818.

Andrew Post, T. Blaine Hoshizaki and Michael D. Gilchrist (2014). "Comparison of MADYMO and physical models for brain injury reconstruction." In: *International Journal of Crashworthiness* 19.3, pp. 301–310. DOI: 10.1080/13588265.2014.897413. eprint: https://doi.org/10.1080/13588265.2014.897413. URL: https://doi.org/10.1080/13588265.2014.897413.

Baker, C E et al. (Dec. 2024). "How Well Do Popular Bicycle Helmets Protect from Different Types of Head Injury?" In: *Annals of Biomedical Engineering* 52.12, pp. 3326–3364.

Collins, Christy L et al. (Oct. 2014). "Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports." In: *The Journal of Primary Prevention* 35.5, pp. 309–319.

Crandall, Jeffrey Richard et al. (2011). "Human surrogates for injury biomechanics research." In: *Clinical anatomy* 24.3, pp. 362–371.

D, Cesari et al. (Nov. 2001). "WorldSID Prototype Dummy Biomechanical Responses." In: *Stapp Car Crash J* 45, pp. 285–318. DOI: doi:10.4271/2001-22-0013.

Delaney, Lacroix, Gagne, and Antoniou (Oct. 2001). "Concussions among university football and soccer players: a pilot study." In: *Clin J Sport Med.* 11, pp. 234–40. DOI: 10.1097/00042752-200110000-00005.

Farmer, Jon et al. (June 2020). "The effect of neck stiffness on the response of a surrogate head due to blunt trauma in judo." In: URL: https://repository.lboro.ac.uk/articles/conference_contribution/The_effect_of_neck_stiffness_on_the_response_of_a_surrogate_head_due_to_blunt_trauma_in_judo/12505805.

— (2022). "A human surrogate neck for traumatic brain injury research." In: *Frontiers in Bioengineering and Biotechnology* 10. ISSN: 2296-4185. DOI: 10.3389/fbioe.2022.854405. URL: https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2022.854405.

FIFA (Mar. 2023). *FIFA Professional Football Report 2023*. Tech. rep. FIFA. URL: https://digitalhub.fifa.com/m/2a5dc95026d9cf8a/original/FIFA-Professional-Football-Report-2023.pdf.

Forero Rueda, Manuel A, Liang Cui, and Michael D Gilchrist (2011). "Finite element modelling of equestrian helmet impacts exposes the need to address rotational kinematics in future helmet designs." In: *Computer methods in biomechanics and biomedical engineering* 14.12, pp. 1021–1031.

Foster, J King, James O Kortge, and Michael J Wolanin (1977). "Hybrid III—a biomechanically-based crash test dummy." In: *SAE transactions*, pp. 3268–3283.

Funk, James R et al. (Nov. 2022). "Best Practices for Conducting Physical Reconstructions of Head Impacts in Sport." In: *Annals of Biomedical Engineering* 50.11, pp. 1409–1422.

Hubbard, R. (1975). "Anthropometric Basis of the GM ATD 502 Crash Test Dummy." In: *SAE Technical Paper 750429*. DOI: https://doi.org/10.4271/750429..

King, Albert I et al. (2003). "Is head injury caused by linear or angular acceleration." In: *IRCOBI conference*. Vol. 12. Lisbon, Portugal.

Kontos, Anthony P. et al. (2016). "Meta-analytical review of the effects of football heading." en. In: *British journal of sports medicine* 51.15, pp. 1118–1124. ISSN: 0306-3674. DOI: 10.1136/bjsports-2016-096276. URL: http://dx.doi.org/10.1136/bjsports-2016-096276.

Krustrup, Peter Krustrup & Birgitte (2018). "Football is medicine: it is time for patients to play!" In: *British Journal of Sports Medicine* 52.22, pp. 1412–1414. ISSN: 0306-3674. DOI: 10.1136/bjsports-2018-099377. eprint: https://bjsm.bmj.com/content/52/22/1412.full.pdf. URL: https://bjsm.bmj.com/content/52/22/1412.

Levy Kasasbeh, Baird, Skeen Amene, and Marshall (2012). "Concussions in Soccer: A Current Understanding." In: *World Neurosurgery* 78.5, pp. 535–544. ISSN: 1878-8750. DOI: https://doi.org/10.1016/j.wneu.2011.10.032. URL: https://www.sciencedirect.com/science/article/pii/S1878875011013064.

Linder, Astrid et al. (2002). "Design and validation of the neck for a rear impact dummy (BioRID I)." In: *Traffic Injury Prevention* 3.2, pp. 167–174.

Luck, JL et al. (2014). "Characterization of the THOR metric neck in tension-bending, anteriorposterior bending." In: *Lateral bending, and torsion; development of injury risk curves and critical values for injury assessment*.

MacGillivray, Samantha et al. (Aug. 2021). "Repeatability and Biofidelity of a Physical Surrogate Neck Model Fit to a Hybrid III Head." In: 49.10, pp. 2957–2972.

Mackay, Daniel F. et al. (2019). "Neurodegenerative Disease Mortality among Former Professional Soccer Players." In: *New England Journal of Medicine* 381.19, pp. 1801–1808. DOI: 10.1056/NEJMoa1908483. eprint: https://www.nejm.org/doi/pdf/10.1056/NEJMoa1908483. URL: https://www.nejm.org/doi/full/10.1056/NEJMoa1908483.

McCunn, Robert et al. (Oct. 2021). “Heading in Football: Incidence, Biomechanical Characteristics and the Association with Acute Cognitive Function—A Three-Part Systematic Review.” In: *Sports Medicine* 51.10, pp. 2147–2163.

Milanović, Zoran et al. (2019). “Broad-spectrum physical fitness benefits of recreational football: a systematic review and meta-analysis.” In: *British Journal of Sports Medicine* 53.15, pp. 926–939. ISSN: 0306-3674. DOI: `10.1136/bjsports-2017-097885`. eprint: `https://bjsm.bmj.com/content/53/15/926.full.pdf`. URL: `https://bjsm.bmj.com/content/53/15/926`.

Nordhoff, Lawrence, Michael Freeman, and Gunter Siegmund (2007). “Comparison of Human and Hybrid III Head and Neck Dynamic Response, SAE Paper No. 861892, Society of Automotive Engineers, Warrendale, PA., 1986.” In: *Human Subject Crash Testing: Innovations and Advances*, pp. 285–305.

Nutt, Shannon et al. (2022). “Neck strength and concussion prevalence in football and rugby athletes.” In: *Journal of Science and Medicine in Sport* 25.8, pp. 632–638. ISSN: 1440-2440. DOI: `https://doi.org/10.1016/j.jsams.2022.04.001`. URL: `https://www.sciencedirect.com/science/article/pii/S1440244022000822`.

Orhant, Emmanuel et al. (2022). “A retrospective analysis of all-cause and cause-specific mortality rates in French male professional footballers.” In: *Scandinavian Journal of Medicine & Science in Sports* 32.9, pp. 1389–1399. DOI: `https://doi.org/10.1111/sms.14195`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1111/sms.14195`. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1111/sms.14195`.

Peek, Kerry, James M. Elliott, and Rhonda Orr (2020). “Higher neck strength is associated with lower head acceleration during purposeful heading in soccer: A systematic review.” In: *Journal of Science and Medicine in Sport* 23.5, pp. 453–462. ISSN: 1440-2440. DOI: `https://doi.org/10.1016/j.jsams.2019.11.004`. URL: `https://www.sciencedirect.com/science/article/pii/S1440244019306607`.

Post, Andrew and T Blaine Hoshizaki (2015). “Rotational acceleration, brain tissue strain, and the relationship to concussion.” In: *Journal of biomechanical engineering* 137.3, p. 030801.

Post, Andrew, Anna Oeur, Blaine Hoshizaki, et al. (2013). “Examination of the relationship between peak linear and angular accelerations to brain deformation metrics in hockey helmet impacts.” In: *Computer methods in biomechanics and biomedical engineering* 16.5, pp. 511–519.

Post, Andrew, Anna Oeur, Evan Walsh, et al. (2014). “A centric/non-centric impact protocol and finite element model methodology for the evaluation of American football helmets to evaluate risk of concussion.” In: *Computer methods in biomechanics and biomedical engineering* 17.16, pp. 1785–1800.

Ridella, S and D Parent (2011). "Modifications to improve the durability, usability, and biofidelity of the THOR-NT dummy." In: *22nd ESV conference, Paper*. 11-0312.

RUSSELL, E. R. et al. (2021). "Association of field position and career length with risk of neurodegenerative disease in male former professional soccer players." In: *New England Journal of Medicine*, pp. 1057–1063.

Sances Jr, A and Srirangam Kumaresan (2001). "Comparison of biomechanical head-neck responses of hybrid III dummy and whole body cadaver during inverted drops." In: *Biomedical sciences instrumentation* 37, pp. 423–427.

Spiotta, Bartsch, and Benzel (Jan. 2012). "Heading in Soccer: Dangerous Play?" In: *Neurosurgery* 70, pp. 1–11. DOI: 10.1227/NEU.0b013e31823021b2.

TAHA, ZAHARI, MOHD HASNUN ARIF HASSAN, and ISKANDAR HASANUDDIN (Aug. 2015). "Analytical modelling of soccer heading." In: *Sadhana* 40.5, pp. 1567–1578. ISSN: 0973-7677. DOI: 10.1007/s12046-015-0383-5. URL: https://doi.org/10.1007/s12046-015-0383-5.

Tarnutzer, A A et al. (2017). "Persistent effects of playing football and associated (subconcussive) head trauma on brain structure and function: a systematic review of the literature." In: *British Journal of Sports Medicine* 51.22, pp. 1592–1604. ISSN: 0306-3674. DOI: 10.1136/bjsports-2016-096593. eprint: https://bjsm.bmj.com/content/51/22/1592.full.pdf. URL: https://bjsm.bmj.com/content/51/22/1592.

Tracey Covassin, C. Buz Swanik and Michael L. Sachs (2003). "Epidemiological Considerations of Concussions Among Intercollegiate Athletes." In: *Applied Neuropsychology* 10.1. PMID: 12734071, pp. 12–22. DOI: 10.1207/S15324826AN1001_3. eprint: https://doi.org/10.1207/S15324826AN1001_3. URL: https://doi.org/10.1207/S15324826AN1001_3.

Ueda, Peter et al. (Apr. 2023). "Neurodegenerative disease among male elite football (soccer) players in Sweden: a cohort study." In: *The Lancet Public Health* 8.4, e256–e265.

Walsh, Evan S et al. (Dec. 2018). "Comparative analysis of Hybrid III neckform and an unbiased neckform." In: *Sports Engineering* 21.4, pp. 479–485.