Development of Novel Non-Pneumatic Tyres to Improve Comfort and Energy Efficiency of Manual Wheelchairs

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Abstract

This project explores Flexible-Spoke Non-Pneumatic Tyres (FS-NPTs) as a new technology to replace conventional wheelchair tyres and improve the quality of life of wheelchair users.

From an engineering perspective, a suboptimal wheelchair tyre means uncomfortable rides, reduced mobility, and increased risk for injury. However, what wheelchair users consider to be an optimal (or suboptimal) tyre has remained relatively unexplored. Wheelchair users experience discomfort due to poor suspension (related to tyre vertical stiffness) and fatigue/injury (related to shear stiffness) due to the drawbacks of current wheelchair tyre technology. These drawbacks include inferior suspension, regular pressure maintenance for optimal performance, and puncture possibility (which severely hinders operation), highlighting the need for new technology. To assess the advantages that FS-NPTs could potentially offer wheelchair users, a method of predicting their mechanical behaviour was required. A systematic literature review on FS-NPT technology was conducted and utilised to inform finite element methods to efficiently design and predict the mechanical response of an FS-NPT with optimal structure (honeycomb structure) based on the design of its internal spokes. To determine the feasibility of this technology, the behaviour of current wheelchair tyre technology required quantification, and so wheelchair pneumatic tyre laboratory tests were conducted to acquire baseline tyre characteristics. To efficiently design an FS-NPT with wheelchair tyre characteristics, a tuning protocol was developed combining Taguchi methods with statistical modelling to design a tyre (through spoke geometry manipulation) that possessed the same vertical stiffness as the wheelchair pneumatic tyre. To fully assess the advantages of this technology, a mixed methods approach was adopted. A questionnaire was developed, and the feedback of 117 wheelchair users was received. The questionnaire findings illustrated that the needs of manual wheelchair users are being compromised by current tyre technology. This research was used to inform the design of the FS-NPT concept. Integrating social science research with mechanical engineering and biomechanics, the needs of wheelchair users were translated into mechanical constraints/objectives, and the tyre was tuned to possess improved values of shear stiffness and mass compared to conventional tyre technology. The final concept produced was a tyre that can provide similar comfort of a pneumatic tyre whilst being easier to propel, and can also provide additional benefits including tyre longevity, low user maintenance, and puncture-resistance. The findings of this project provide a strong foundation to develop and implement this technology in the future to improve the quality of life of wheelchair users.

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Author's Declaration

This thesis is the result of the author's own work and has not previously been submitted for any other degree at the University of Staffordshire or another institution.

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Chapter 1: Introduction

1.1 Background

The self-propelled manual wheelchair that is recognised today was invented in 1869 and was built with the purpose of providing wheeled mobility and seated support for a person with difficulty in walking or moving around [1]. Gradual improvements were made to this wheelchair over the years including the addition of push rims and spokes to the wheels, but those credited with inventing the modern manual wheelchair were Harry Jennings and Herbert Everest. These two mechanical engineers developed the first lightweight, foldable, and self-propelled wheelchair in the early 1930s (Figure 1.1) [2].

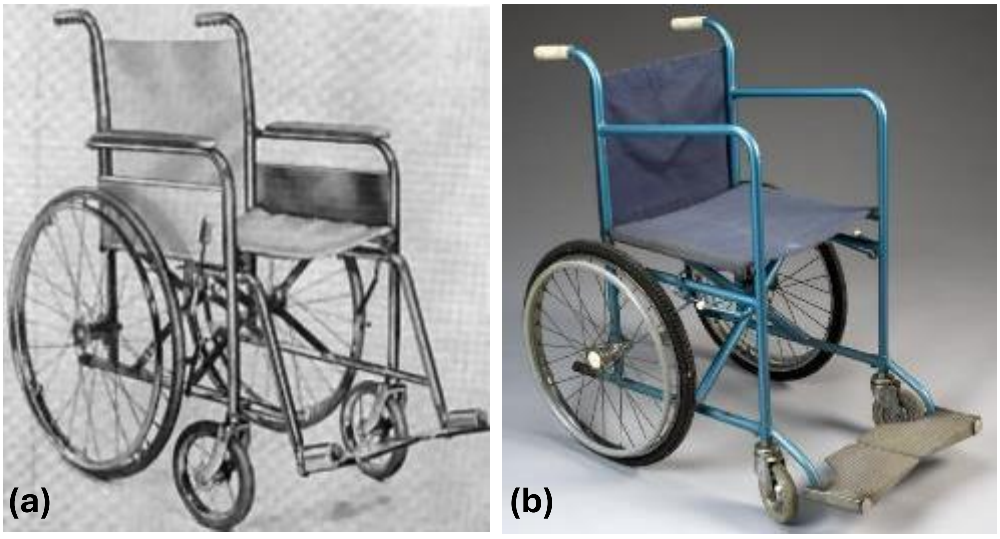


Figure 1.1 - (a) Concept of the 1930s foldable manual wheelchair by Jennings and Everest reprinted from [3]. (b) Model 8 version of this wheelchair built in the 1950s reprinted from [4]. Figure adapted by author.

The wheelchair (and manual wheelchairs to this day) uses two types of wheels: caster wheels at the front, and drive wheels at the rear of the wheelchair (details of wheelchair and wheel/tyre types are presented in sections 2.2 and 2.3). The rear wheel tyres of the first modern wheelchair were likely solid; the introduction of pneumatic tyres to wheelchair technology is suggested to have been around the early to mid-20th century. Since the development of this wheelchair, innovation has resulted in lighter materials and more ergonomic components being introduced, but the fundamental structure and purpose of this wheelchair has remained very similar. This also applies to the tyres, where the only tyre options are either pneumatic or solid non-pneumatic.

The needs of manual wheelchair users are complex and differ from person to person. Literature on wheelchair user needs demonstrates that they desire a wheelchair that is comfortable and easy to propel [1]. As the standard manual wheelchair does not have a suspension system, the only suspension provided is through the tyres and sometimes the cushioning of the seat. Therefore, tyre choice is an important decision, and users frequently select rear wheel pneumatic tyres due to their light weight, high wheeling efficiency, and shock absorbing abilities, in order to satisfy their needs. However, pneumatic tyres have limitations, the most important of which is the fact that they can get punctured [5]. This can be a debilitating experience for wheelchair users as it can result in them becoming stranded, and it can also increase the risk of injury due to the need for more exertion to move the wheelchair. Furthermore, the internal pressure of pneumatic tyres reduces overtime, losing up to 40% of pressure per month, resulting in reduced wheeling efficiency [6]. This leads to an increased energy demand for users to propel themselves and increases the risk of injury by overexertion [6,7].

Innovation in the area of wheelchair tyres in more recent years has produced pneumatic tyres with internal foam, anti-puncture lining/sealants or tyre inserts to address the disadvantages of pneumatic tyres. These tyres mitigate the risk of punctures, but they are costly and are heavier which negatively affects tyre performance [8].

Solid non-pneumatic tyres made of compact material such as rubber are the only widely available alternative to pneumatic tyres. These tyres typically last longer than pneumatic tyres as they cannot puncture and require little to no maintenance. However, they generally have lower wheeling efficiency, and they are heavier. They also have lower shock absorbing abilities which leads to impact loads and vibrations from obstacles such as kerbs and uneven terrain being mostly transmitted to the user. This compromises user comfort, which can also result in pain/injury [9].

As a result of the limitations of current tyre technologies available on the market, wheelchair users either have to compromise on comfort and wheeling efficiency with solid non-pneumatic tyres, or risk punctures and have to maintain pressure regularly with pneumatic tyres. These compromises can lead to suboptimal performance and even increase the risk for injuries. According to literature, shoulder or wrist pain caused by the use of suboptimal wheelchairs are highlighted as major risks for the loss of independence, which can lead to issues with mental health from isolation/dependency and negatively impact quality of life [6,10]. At the same time, this long-term adherence to established tyre technologies (pneumatic or solid non-pneumatic) means that opportunities for enhanced wheelchair performance through new technologies have mainly remained unexplored.

In more conventional engineering applications such as automotive, aerospace and others, Flexible Spoke Non-Pneumatic Tyre (FS-NPT) technology is suggested to provide the benefits of pneumatic tyres without the drawbacks of pneumatic or solid non-pneumatic tyres (example FS-NPT shown in Figure 1.2). However, their use has not yet been explored in wheelchairs. These tyres also have the capacity for tuning their mechanical behaviour via the material and geometry of the spokes, which suggests they can be adapted to the specific requirements of individual users. In the case of wheelchairs, this tuning could allow optimum comfort and wheeling efficiency which will positively contribute towards wheelchair user satisfaction and improve their quality of life. Regarding their identified disadvantages, current literature highlights excessive vibrations and an inability to dissipate heat at high speeds (+50mph) [12]. No disadvantages are noted in literature for low-speed applications. Based on these, FS-NPTs appear to have strong potential to enhance the mechanical behaviour of wheelchairs and to address the individual needs of wheelchair users.

Figure 1.2 - Image of an automobile FS-NPT reprinted from [11]

1.2 Aims and Objectives

Building upon this foundation, the aim of this PhD thesis is to explore the potential use and value of FS-NPT technology in wheelchairs. FS-NPTs are currently being used in a range of different applications, however, it is unclear whether this technology can be effectively adapted for use in wheelchairs and whether it could offer any significant improvement compared to existing wheelchair tyres. This PhD thesis is the first to scientifically study the applicability of FS-NPTs in wheelchairs aiming to develop concepts for FS-NPT design and their personalisation/tuning, as well as to explore further potential benefits that such tyres can offer to wheelchair users.

Exploring whether FS-NPTs can meet the identified user needs requires a capacity to predict tyre behaviour and to quantify the optimum set of design parameters. Being able to accurately predict the behaviour of FS-NPTs can open the way to directly test whether they are indeed a good candidate technology for wheelchair applications. To this end, it is fair to assume that if FS-NPTs are indeed a good candidate technology for wheelchair applications, then they should be able to replicate key mechanical characteristics of existing pneumatic tyres and also offer improvements that are deemed important by their users.

In this context the specific objectives of this PhD project are:

- Objective 1. To develop a methodology to predict the mechanical behaviour of an FS-NPT based on the design of its spokes.
- Objective 2. To test whether FS-NPTs can replicate the mechanical characteristics of existing wheelchair tyres.
- Objective 3. To explore the potential improvements to user experience that wheelchair FS-NPTs could offer.

To meet these objectives, computer modelling, and lab-based testing will be combined with a first of its kind qualitative assessment of wheelchair user needs and experience regarding their tyres to explore whether wheelchair FS-NPTs are likely to achieve improvements that matter to their users.

Key elements of literature that were used here to support the aim and objectives of this thesis are discussed in subsequent chapters. The following section outlines the chapters of this thesis and the work which contributes towards meeting the specific objectives.

1.3 Outline of Thesis

The schematic in Figure 1.3 presents the chapters and objectives of the thesis.

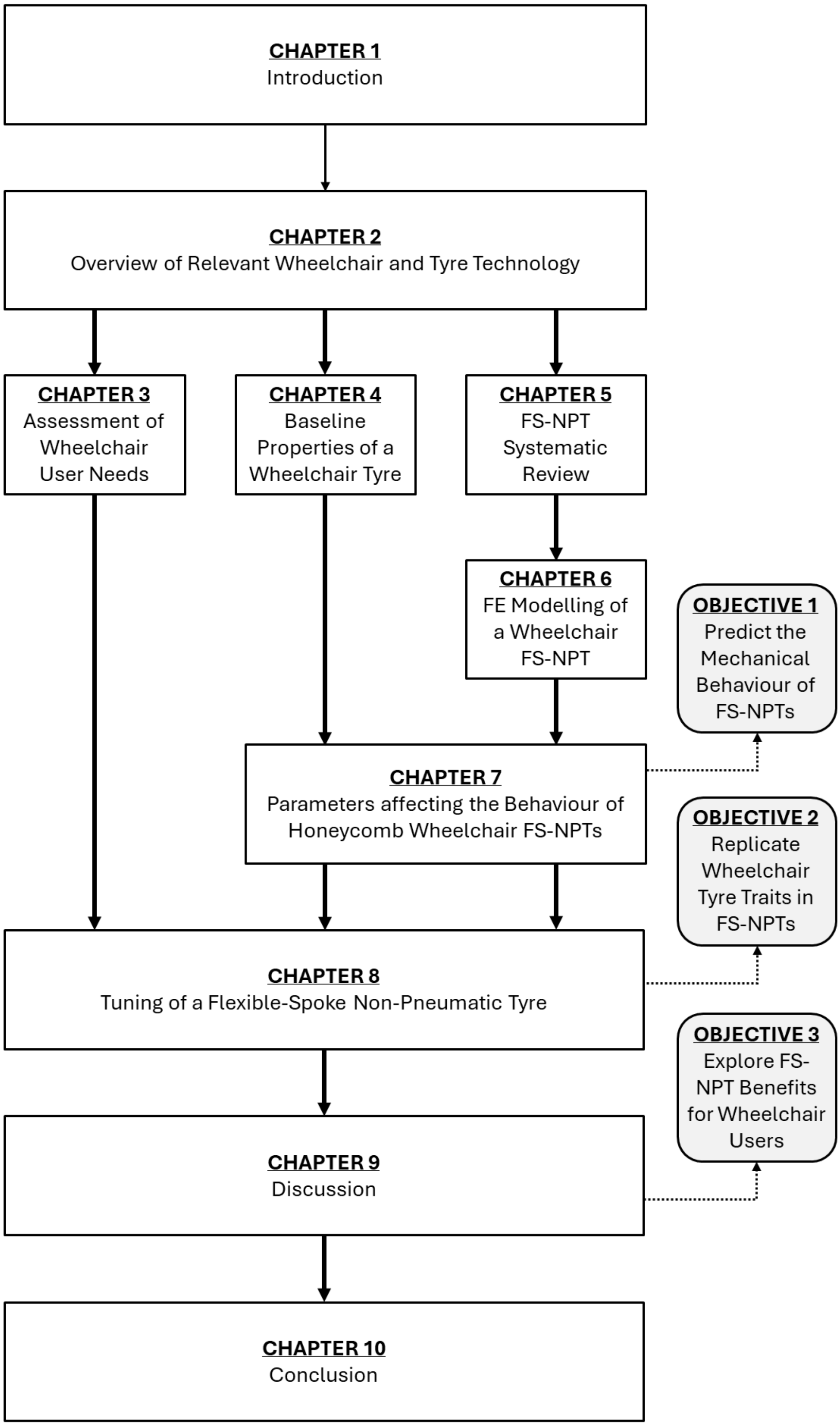


Figure 1.3 - Schematic illustrating how each chapter builds towards fulfilling the objectives of the thesis.

Figure 1.3 highlights the flow of work, it illustrates how individual chapters are connected and combined, and where the objectives are met. The chapters are further explained below.

Before assessing the needs of wheelchair users, an understanding of the technology that is currently available relative to this research project is required. Chapter 2 provides an overview of wheelchair and tyre types currently available to wheelchair users, and also provides an overview of existing FS-NPTs in literature.

To meet the objectives of this PhD project, a deep understanding of wheelchair user needs is required. In Chapter 3, the perceptions of wheelchair users about their needs and requirements for optimum wheelchair experience are investigated using an online questionnaire that was developed for this purpose. The information collected here frames the discussion of results in subsequent chapters and ultimately enables conclusions to be drawn on whether FS-NPTs are likely to offer improvements that matter to wheelchair users.

Before in-depth studying of FS-NPTs, the mechanical characteristics of conventional pneumatic tyres needs to be understood to provide baseline properties that can be used to inform the design of a wheelchair FS-NPT. Chapter 4 discusses an experiment on a standard manual wheelchair with conventional pneumatic tyres which was conducted to obtain the baseline mechanical properties of a pneumatic wheelchair tyre, specifically vertical stiffness, shear stiffness, and mass.

To support the experimental and computational work to follow, 0 focuses on literature about FS-NPT technology. A systematic literature review is conducted specifically aimed at literature on Finite Element (FE) modelling of FS-NPTs. Existing FS-NPT designs were categorised into groups and the most prominent of those was identified for use in the rest of the thesis (i.e. honeycomb design).

In Chapter 6, segments of a theoretical FS-NPT were 3D-printed utilising spoke designs that were defined in the FS-NPT systematic review. These segments were mechanically tested to obtain the experimental data required to identify and validate the optimum FE modelling strategy to simulate these novel structures.

Following validation of individual spoke models, a parametric FE model of a complete FS-NPT was created to enable estimating its mechanical behaviour in Chapter 7 (Objective 1 met). To efficiently determine the geometric parameters which affect tyre behaviour, a parametric FE analysis was performed using the Taguchi robust experiment design method. The statistical significance and influence of different spoke design parameters were quantified to allow prediction of individual geometric parameters on the behaviour of a complete FS-NPT.

The FE models in Chapter 6 and Chapter 7, and the significant parameters identified in Chapter 7Chapter 6 were used in a series of virtual experiments in Chapter 8. The results from these simulations were used in a multiple linear regression analysis to produce coefficients in attempt to predict the tyre mechanical behaviour without the need for FE modelling. This new information provided the necessary knowledge to tune the design of the wheelchair FS-NPT model to test whether it can replicate the mechanical properties of a standard wheelchair pneumatic tyre (from Chapter 4) and for the first time prove the feasibility of a wheelchair FS-NPT (Objective 2 met). This also allowed tuning of the FS-NPT to provide potential improvements over existing tyre technology (i.e. lower mass).

A discussion of the entire thesis relative to the objectives is made in Chapter 9. In this chapter, the key findings from previous chapters are collated to assess whether FS-NPTs could offer improvements over current tyre technology that matter to wheelchair users. Data from the questionnaire (Chapter 3) was combined with numerical findings to determine whether the apparent characteristics of wheelchair FS-NPTs align with the users' perceived needs (Objective 3 met).

In Chapter 10, the key findings of the entire thesis are presented, and the current interpretation of the findings along with the potential broader impact are discussed. Gaps in literature and contribution to knowledge are presented, and recommendations and future work are discussed.

The work of this thesis involves a mixed methods approach which is apparent in the schematic (Figure 1.3) and the description of chapters. Social science research (assessment of wheelchair user needs through a questionnaire) is combined with engineering analyses (FE modelling and tuning) to achieve the aim and objectives of the thesis.

Chapter 2: Overview of Relevant Wheelchair and Tyre Technology

2.1 Introduction

There are various types of wheelchairs and tyres that are currently available to wheelchair users. A multitude of wheelchairs exist to accommodate for the different needs of wheelchair users. For example, a self-propelled wheelchair is tailored to users with sufficient upper body strength to allow self-propulsion, whereas attendant propelled wheelchairs are more suitable for users who struggle with manual exertion. The different types of wheelchairs should be explored to understand the technology that is currently available and to also to aid in assessing whether FS-NPTs are potential candidate technology. Understanding wheelchair tyre technology is also fundamental in determining whether FS-NPTs can replicate or provide superior performance to conventional technology, from an engineering perspective.

There also exists a multitude of FS-NPT types which exhibit various mechanical behaviours and are therefore used in various applications. Understanding current technology and identifying the advantages and disadvantages is a required foundation to determine whether FS-NPTs are applicable to wheelchairs applications.

This section therefore outlines key technologies that build on the information presented in Chapter 1 and also supports the subsequent work throughout the thesis.

2.2 Wheelchair Technology

This section focuses on the different types of available wheelchair technology and delves deeper into wheel/tyre types and their functionalities.

A wheelchair is a device that provides wheeled mobility and seated support for a person with difficulty in walking or moving around [1]. There are two main types:

- Manual – Fully or partially propelled by the user or attendant. These can be divided into four sub-categories: Standard wheelchairs that can be pushed or propelled (Figure 2.1a), active wheelchairs (Figure 2.1b), transit wheelchairs (Figure 2.1c), and power-assisted wheelchairs (Figure 2.1d).
- Fully motorised – Battery operated wheelchairs controlled by the user (Figure 2.1e).

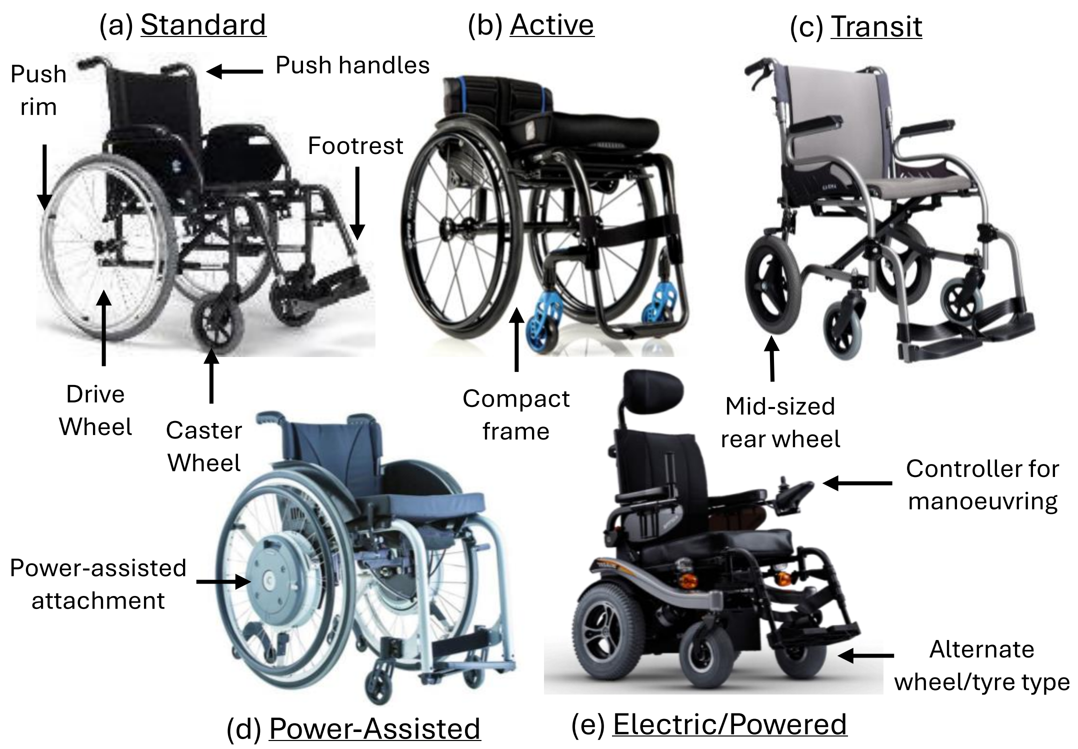


Figure 2.1 - (a) Standard manual wheelchair adapted from [13], (b) Active manual wheelchair adapted from [14], (c) Transit manual wheelchair adapted from [15], (d) Power-assisted manual wheelchair (attached to active wheelchair type) adapted from [16], (e) Fully motorised wheelchair (electric/powered) adapted from [17].

The standard manual wheelchair is the most common wheelchair (Figure 2.1a). It is often used as a short-term use wheelchair in locations such as supermarkets and hospitals [10]. It has push rims mounted to the wheels so that users can propel themselves, and it also has upper rear backrest handles so an attendant can assist with propulsion. It uses two very different types of wheels: caster wheels, and drive wheels. This wheel/tyre arrangement is the same for active and some power assisted wheelchairs (wheel/tyres are further discussed in section 2.3). Many standard wheelchairs have adjustable footrests, seats, and headrests to help the user fit properly inside and feel comfortable [10].

Active wheelchairs are similar to standard wheelchairs utilising a similar structure and wheel arrangement, but the major difference is the design which accommodates users who are fully independent and can propel themselves. These wheelchairs are manufactured to be lightweight and compact so that users can propel themselves efficiently for long periods of time, and to enable them to easily lift and store their wheelchair (the active wheelchair in Figure 2.1b can weigh as little as 6kg compared to the 17kg mass of the standard wheelchair in Figure 2.1a). These wheelchairs are usually custom-made and designed to fit to individual user dimensions so that the wheelchair is comfortable, lightweight, and generally as ergonomic as possible. However, they are more costly due to this custom process, as well as the use of strong, lightweight materials in the frame and wheels such as carbon fibre [18].

A transit wheelchair (Figure 2.1c) is a manual wheelchair designed for attendant propulsion only and is used normally for short term use. The mid-sized rear wheels make it lighter and easier to manoeuvre, but consequently, they cannot have mounted push rims for user self-propulsion.

A power assisted wheelchair can be any type of manual wheelchair but with an electric motor that assists with propulsion (Figure 2.1d shows an active manual wheelchair with a power-assisted attachment). A battery (usually positioned under the seat) provides power to motors attached to the wheels which assists in the propulsion of the wheelchair, and the user can control the desired amount of propulsion they require [19]. Wheeled motor attachments can also be attached at the front or the back of wheelchairs to assist with propulsion (useful in the case of transit wheelchairs). These attachments are highly beneficial for users who seek independence but may have trouble with manual propulsion due to weakness, fatigue, injury, or medical illness.

An electric wheelchair is a fully motorised wheelchair which eliminates the need for manual propulsion or attendant assistance. They are heavier than manual wheelchairs as they require a battery for operation and usually have a suspension system due to the higher net weight. They are useful to users when they are travelling long distances, over rough terrain, or want to travel quickly, but due to their size and weight, it is harder to transport an electric wheelchair without a specialised vehicle [19]. Sometimes, these wheelchairs are the only option for independence to users who are unable to manually propel themselves.

Wheelchair technology has been classified into various types over the years due to the prevalence and innovation of technology, and Figure 2.1 is deemed to be an accurate representation of the main wheelchair types. Regarding the usage of each type, a UK survey conducted in 2005 with a sample size of 1356 found that 42% used a self-propelled wheelchair (manual and active), 27% used an electric wheelchair, 18% used a mobility scooter, and 13% used an attendant propelled wheelchair (transit) [20]. There was no data collected on power-assisted wheelchairs. Previous studies from 1999 and 1991 demonstrated that manual wheelchairs were the most common type of wheelchair, and the percentage of electric wheelchair users is increasing [21,22]. Mobility scooters were excluded from this outline of wheelchair technology as they are not classed as a wheelchair (and are usually a part-time convenience technology rather than an assistive device prescribed by a healthcare professional).

2.3 Wheelchair Wheel and Tyre Technology

The aforementioned wheelchair types employ various types of wheels and tyres. The wheels attach to the frame of the wheelchair and allow rotation in one or more axes, and the tyres attach onto the external surface of the wheel and mainly provide traction and suspension. Each of these wheels/tyres have different purposes which provide various properties and are explained here.

Manual wheelchair pneumatic tyres comprise a thin outer rubber layer which encloses onto the wheel rim, and an internal (inner) tube that is inflated with air (Figure 2.2a), although some tyres operate without this tube (tubeless). The internal air provides suspension support when the tyre is subjected to loading via compression of the air and the tyre returns to its original shape after unloading. Due to most of the tyre consisting of air, it is also lightweight, which means a lower moment is required to overcome inertia and propel the wheel/tyre and thus a higher wheeling efficiency is achieved. Wheeling efficiency (aka. propulsion efficiency, energy efficiency) is defined as the ratio of the propulsion input from the user (attempting to rotate the wheels to propel the wheelchair), and the resultant propulsion of the wheelchair. This can be measured by recording the oxygen expenditure of a participant during one wheeling cycle, and the distance the wheelchair moves [6]. Wheeling efficiency can never be 100% due to energy loss in friction etc., but pneumatic tyres generally have ‘high’ wheeling efficiency due to the low weight and the ease of navigating obstacles. However, the internal air pressure of pneumatic tyres reduces overtime mostly due to permeation [5] which hinders their operational properties including their ability to absorb shocks and efficiently propel. Also, puncturing the inner tube (or the outer rubber layer in tubeless tyres) will lead to a flat tyre which provides no suspension and severely reduces wheeling efficiency. To prevent this occurrence, some pneumatic tyres are fitted with anti-puncture lining/sealants or tyre inserts to eliminate the disadvantages of pneumatic tyres. However, these features add weight to the tyre which reduces wheeling efficiency and causes other negative effects on tyre performance.

Solid non-pneumatic tyres (or airless tyres) are the only existing alternative to pneumatic tyres. These can be solid material or foam filled, and by definition, they do not rely on internal pressurised air for their operational properties. Manual wheelchair solid tyres (Figure 2.2b) usually comprise compact solid rubber which means they have little suspension properties except for small compressions of the rubber itself (in Figure 2.2b, the inner surface of the tyre is solid compared to the hollow structure of the pneumatic tyre). They are also usually heavier and have higher rolling resistance according to literature [6,23]. More specifically, one study measured the mass of a pair of solid tyres to range from 1 to 1.44kg, whereas pneumatic tyres weighed 0.74 to 1.26 kg [6], conveying that pneumatic tyres are generally lighter, but it can depend on the specific type of tyre. The difference between the lightest and heaviest of the aforementioned tyres (0.7kg) will likely make noticeable differences to active wheelchair users with ultra-light wheelchairs weighing 6kg (potentially increasing the net weight by 12%), suggesting the importance of minimising tyre weight. The benefits of these tyres include high durability, little to no maintenance, and puncture resistance. Foam filled tyres can be classed as solid or semi-pneumatic tyres as they utilise a pneumatic tyre carcass, but the internal volume is filled with foam instead of air. The foam provides suspension support and like solid tyres, does not require maintenance and is puncture proof. However, the foam is heavier than air which would likely negatively impact wheeling efficiency.

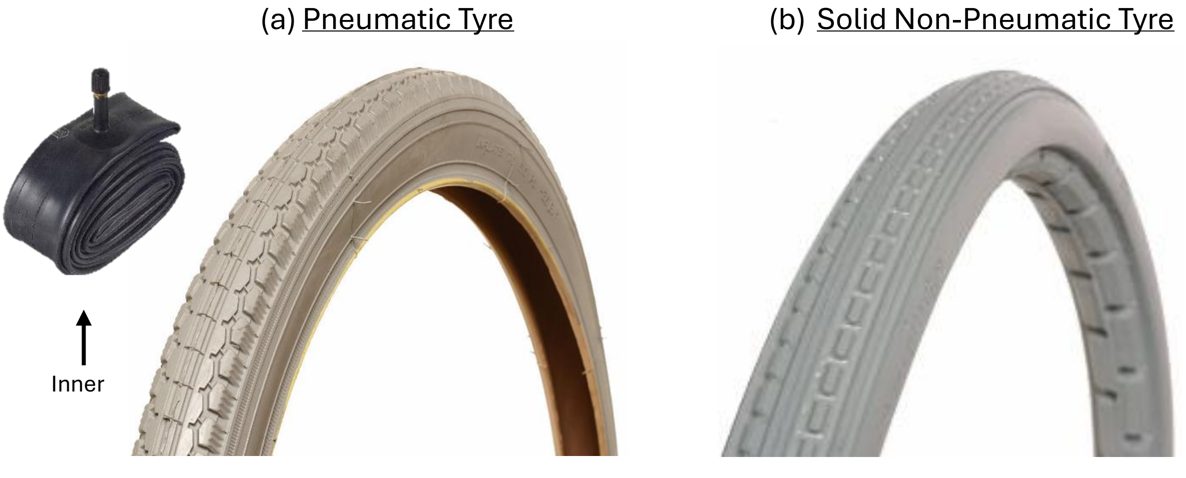


Figure 2.2 - The two types of wheelchair tyres: (a) Pneumatic tyre reprinted from [24] and inner tube reprinted from [25] (b) Solid non-pneumatic tyre reprinted from [26]. Figure adapted by author.

Manual wheelchair drive wheels are situated towards the rear of the wheelchair, they are larger than the front caster wheels, and are fixed to one axial plane. Standard and active wheelchair drive wheels can consist of large composite spokes (Figure 2.3a) or thin metallic spokes (Figure 2.3b) which connect from the axle to the wheel outer rim. These spokes are practical as they ensure the wheel is rigid with minimal material and thus minimal weight. These wheels have either solid non-pneumatic or pneumatic tyres mounted onto the wheel rim. The purpose of these wheels is to allow propulsion of the wheelchair by the user (via mounted push rims), and they also greatly contribute to the comfort and propulsion efficiency of a wheelchair, depending on the tyres used. Transit wheelchair rear wheels (Figure 2.3c) are smaller than standard and active rear wheels; this allows them to be lighter and more manoeuvrable but consequently cannot be propelled by the user. All wheelchairs tend to have caster wheels at the front which are small and are able to rotate in a 360° range to help with direction changes and overall manoeuvrability (Figure 2.3d). These wheels are usually made of a type of plastic and have an external solid rubber (or similar polymer) tyre, but there are pneumatic variants. The wheels of fully motorised wheelchairs are usually wider and utilise stiffer materials such as metals to effectively carry the weight of the electric wheelchair (Figure 2.3e and f). Like other wheelchair types, the front wheels tend to have solid-non pneumatic tyres and the rear wheels can be solid or pneumatic. The choice of pneumatic or solid tyres may seem less significant to a powered wheelchair user as the suspension system will greatly improve their comfort, and the wheeling efficiency of the tyres will only impact battery/motor performance.

Figure 2.3 - Wheelchair wheel types: (a) Manual drive wheel with composite spokes reprinted from [27]. (b) Manual drive wheel with metallic spokes reprinted from [28]. (c) Transit rear wheel reprinted from [29]. (d) Manual caster wheel reprinted from [30]. (e) Electric rear wheel reprinted from [31]. (f) Electric front caster wheel [32]. Figure adapted by author.

The presented information on wheelchair technology outlines specific features of each wheelchair type. Fully motorised wheelchairs have a suspension system that provides shock absorption, and the wheelchair is propelled by a motor, whereas manual wheelchairs do not have a suspension system and propulsion requires physical input from the user. This would suggest that FS-NPTs would be most beneficial for manual wheelchair users as they can potentially increase comfort by simultaneously providing more suspension than solid tyres and higher wheeling efficiency. Assessment of manual and electric wheelchair user needs is required to validate this and determine the target audience for which FS-NPTs would be most beneficial. Furthermore, for an FS-NPT to be competitive with current tyre technology, this tyre should be able to be mounted onto the wheel rim of standard wheelchair wheels (such as the wheels shown in Figure 2.3a and b). This ensures that wheelchair users do not have to purchase a unique wheel but instead can use their existing wheels of which the FS-NPT can be directly mounted on to by users themselves or a wheelchair manufacturer.

2.4 Flexible-Spoke Non-Pneumatic Tyre Technology

FS-NPTs are an emerging technology in the transport sector and are present in multiple engineering disciplines such as civil, military and aerospace [33]. These tyres have the ability to support vehicles/equipment without the need for air pressure, and instead use elastic spokes. Whilst the term ‘spoke’ is often used for the metallic/composite struts which connect from a typical wheelchair wheels’ central hub to the outer wheel rim, it is also commonly used in literature to describe the plate configurations that make up the design of a non-pneumatic tyre, for example, a honeycomb spoke design. In this thesis, the terms ‘spoke’, or ‘flexible spoke’ will refer to the spokes of a non-pneumatic tyre (spoke difference is highlighted in Figure 2.4).

The demand for FS-NPT technology originated from the current drawbacks of conventional tyre technology. Solid and pneumatic tyres have been available for a long time, and for a new tyre to compete with this technology, it would ideally have the advantages of both of these tyres (e.g., high comfort, high wheeling efficiency, puncture proof, durable, low maintenance).

FS-NPTs have been subject to extensive research over recent years in order to meet and surpass current tyre standards. They can eliminate pneumatic tyre disadvantages as they do not contain air and therefore cannot puncture or blow out, and also do not require pressure maintenance. Some varieties of these tyres are also hypothesised to have the ability to tune directional stiffnesses separately via changing the spoke geometry, allowing for advantageous properties that are unavailable simultaneously in current tyre technology [34]. However, the main drawback of FS-NPTs is the large build-up of heat due to excessive vibration of the elastic spokes when used on high-speed vehicles (which would normally be dissipated within the air of a pneumatic tyre)[35]. As researchers work to develop FS-NPTs which are suitable for high-speed vehicles, other researchers/manufacturers have explored and implemented these tyres onto lower speed applications where this problem is not an issue [36].

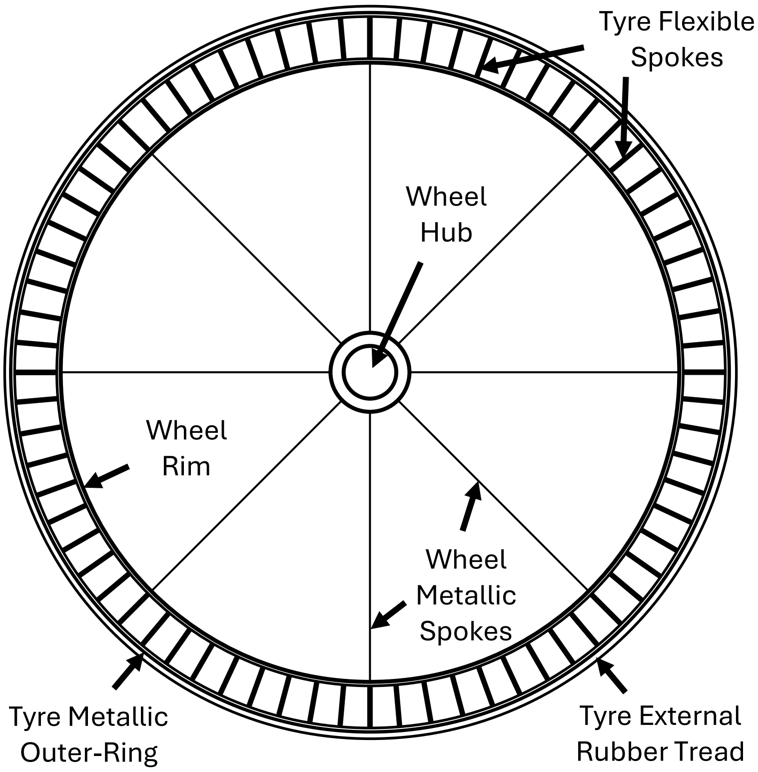


Figure 2.4 - FS-NPT with simple radial spoke structure and standard manual wheelchair wheel schematic.

FS-NPTs consist of multiple deformable hyper-elastic spokes (usually of polymeric material) that replicate the behaviour of the internal air pressure in pneumatic tyres. A typical FS-NPT structure is shown in Figure 2.4 and comprises flexible spokes, an external rubber tread, and an outer-ring that is sandwiched between the spokes and the tread [37]. The outer-ring maintains the structural integrity of the tyre and has a very small thickness, and the tread is responsible for providing grip/traction. These tyres can have varied structured spokes which can influence the performance of the tyre (a radial spoke structure is shown in Figure 2.4 for simplicity).

There are several types of applications where FS-NPTs are currently being used. Bridgestone corporation have developed an airless tyre which is intended for bicycles and slow vehicles such as golf carts (Figure 2.5a) [38]. Bicycle pneumatic tyres require pressure maintenance and are prone to punctures, but these tyres eliminate these drawbacks and claim to “use resources more efficiently”. However, they are currently more expensive than regular bicycle tyres but are also more durable and should therefore have increased longevity and be cost-worthy over time.

The properties that FS-NPTs possess make them an excellent candidate for heavy duty construction vehicles [39], and Michelin are working on FS-NPTs in this sector [40]. The vertical stiffness of these tyres can be tuned to possess high load-bearing properties which are a necessity for transporting heavy loads. The Tweel (combination of tyre and wheel) by Michelin (Figure 2.5b) was initially intended to be used on road vehicles, but due to its excessive noise and vibration of the spokes at high speeds (50 mph+), it was deemed unsafe as this leads to a build-up of heat which causes the tyre to behave undesirably [12]. However, UPTIS (Unique Puncture-proof Tire System) is another FS-NPT concept by Michelin (Figure 2.5c) and with the help of General Motors, they predicted it would be ready for road vehicles in 2024 [11]. These spokes are made out of glass-fibre reinforced polymer unlike the polyurethane Tweel, and additive manufacturing can be used to build a part of the tyre. A further improvement compared to pneumatic tyres is its durability, and lateral stability as there is no sidewall that can be deformed, and the contact region stays the same due to the shape of the tread. These tyres are likely to be more expensive than current automotive pneumatic tyres but again should be cost effective due to their longer life, which also reduces waste. However, a drawback of FS-NPTs is once they are manufactured, they cannot be re-tuned [41,42].

There have been many casualties in war due to vehicles becoming immobile due to damage to the pneumatic tyres from IEDs, gunfire or shrapnel [33]. Resilient Technologies have worked with the military to prevent these disasters through implementation of FS-NPTs [41]. They normally consist of a honeycomb design (Figure 2.5d) which is not built for high speeds but instead has high damage resistance. Polaris Industries design military grade vehicles such as all-terrain vehicles (ATVs) that include resilient FS-NPTs built to withstand warfare [43]. A notable mention is the NASA non-pneumatic tyre developed in the 1970s for the lunar roving vehicle, however this relied on the deformation of chainmail rather than flexible spokes [44].

Figure 2.5 – FS-NPT Applications: (a) Bridgestone FS-NPT on a bicycle reprinted from [36]. (b) Tweel on construction vehicle reprinted from [45]. (c) UPTIS on a passenger vehicle reprinted from [11]. (d) Honeycomb FS-NPT on a military vehicle reprinted from [46]. Figure adapted by author.

According to their applications, FS-NPTs have the potential to provide an improvement over conventional wheelchair tyre technology and enhance wheelchair user satisfaction, but further research is needed to determine their full potential. These aforementioned applications all utilise a large spoke area compared to the flexible spoke area shown in Figure 2.4 (which represents the height of current wheelchair tyre technology), and so this is a challenge that needs to be explored if FS-NPTs are to be adapted onto existing wheelchair wheels.

2.5 Conclusion

This chapter outlined key technologies that are relevant to the thesis, namely wheelchair technology, wheelchair wheel and tyre technology, and FS-NPT technology. Whilst FS-NPTs appear to be a potential candidate technology for wheelchairs from an engineering perspective, it is not clear whether they are able to meet the specific requirements of wheelchair users. The needs of wheelchair users must be explored via in-depth investigations to determine whether FS-NPTs are indeed a suitable technology.

Chapter 3: Assessment of Wheelchair User Needs

3.1 Introduction

The needs of wheelchair users are complex and differ from person to person. User needs can depend on lifestyle, medical conditions, environment, and other factors. The general and specific needs of wheelchair users should be explored to determine what these needs are, and to determine barriers that could be preventing their needs from being met. The next section contains a review of literature relating to wheelchair user needs and potential barriers.

3.1.1 Literature on Wheelchair User Needs

The purpose of this review was to determine the needs of wheelchair users. Relevant sources were considered as studies which have attempted to identify the needs of wheelchair users and/or addressed barriers, studies that have focused on the quality, maintenance, mechanics, and other potential aspects of wheelchairs, and any questionnaires/surveys obtaining feedback from wheelchair users themselves (or relevant experts).

The synthesised literature highlighted key themes among this research area. The most common method for assessing user needs in literature was the utilisation of questionnaires/surveys to obtain feedback from wheelchair users or relevant experts themselves. Most studies focused solely on manual wheelchairs, with many incorporating both types and few focusing only on electric wheelchairs. Key themes of studies in literature included identifying wheelchair user needs, wheelchair user satisfaction, wheelchair stability, wheelchair maintenance/repairs, wheelchair prescription, and wheelchair user associated pain.

Many studies aimed to characterise wheelchair user needs; these are sometimes presented in terms of wheelchair characteristics that are required to meet the needs of wheelchair users. The Guidelines on the provision of manual wheelchairs in less resourced settings [1] states that a suitable wheelchair is one that meets five key criteria: it is appropriate for the environment in which the user operates it; it provides a proper fit and adequate postural support; it is safe and durable; it is available within the country; and it can be obtained, maintained, and afforded by the user. It also states that: “A wheelchair that is functional, comfortable and can be propelled efficiently can result in increased levels of activity. Independent mobility and increased physical function can reduce dependence on others." This highlights comfort and high propulsion efficiency as two important needs of wheelchair users which contribute towards user independence. Naniopoulos et al [47] characterised user needs into 5 areas which were safety, manoeuvrability, comfort, acceptability, and viability, which closely align with the aforementioned study. These needs become more pronounced when one considers the dependence on this technology that many users have. On average, manual wheelchair users spend 11 hours in their wheelchair, travel 2 km, and spend 1 hour on the move per day [48]. This highlights the need for this technology to be up to a high standard to ensure maximum quality of life for wheelchair users.

Several studies focused on obtaining feedback from wheelchair users to determine their satisfaction levels with their current wheelchair technology, which can contribute towards identifying their needs (and whether they are being met), and also highlight areas that require improvement. Fitzgerald et al (2005) explored issues in maintenance and repairs of wheelchairs and sought user feedback [49]. Results from a questionnaire showed that out of 110 participants, 27% had had tyre problems in the past 6 months and 19% had new tyres in the past 6 months. Most users were satisfied with their wheelchairs, but repairs/maintenance would negatively affect their satisfaction, with tyres being a key contributor to this. Marchiori et al (2015) also used a questionnaire to determine wheelchair user satisfaction and found that most users indicated a good level of satisfaction with their manual wheelchair, but some aspects of the wheelchair such as dimensions and push handles could be optimised [50].

The stability of manual wheelchairs in particular is an important characteristic which can aid with kerb mounting/dismounting and can also influence other wheelchair characteristics. Moody et al (2012) studied the effect of stability in wheelchairs [52]. Loss of wheelchair stability can lead to a chair tipping and potential injury to the user including sixteen fatalities reported between 2005 and 2007, and 12% of users experience a tip per year. It was discovered that high levels of stability can cause issues with propulsion and manoeuvrability, but low stability can cause the wheelchair to tip. There should therefore be a balance, however, the NHS test for static stability involves a fixed angle at 12° for manual wheelchairs with a pass or fail criteria. This test negatively impacts user propulsion which compromises users basic need to propel their wheelchair efficiently. In further research by Moody et al [53], their findings show that not all wheelchair users receive a stability test, and stability testing methods and wheelchair prescription require improvement. They also state that "all wheelchair users would benefit from their wheelchair being tuned to their individual needs and capabilities". This supports the notion that wheelchair users' needs differ from person to person, and whilst generalised needs can be extracted from literature findings, the optimal solution for maximum user satisfaction is to accommodate wheelchair technology (including tyres) to individuals themselves. This is a limitation of current clinical methods and could also be viewed as a limitation of current wheelchair tyre technology. Many parts of a wheelchair are customisable to suit an individual users' needs, but there is typically a limited selection of tyres that users must choose from These may not necessarily be optimal to their specific needs, and whilst pressure manipulation can be used to tune the tyres to better suit them, this is a trial-and-error process, and it is one that is difficult to maintain (as pressure levels can fluctuate and diminish over time).

Maintenance of wheelchairs is crucial to ensure that they are delivering maximum performance to the user to ensure their needs are being met, and improper maintenance can cause user injury. Withrington et al (1985) examined hospital manual wheelchairs and found that 57% of wheelchairs with pneumatic tyres had some sort of tyre defect (37 were under-inflated, 16 were punctured) [54]. A basic need of wheelchair users is to have properly inflated tyres for efficient propulsion and comfort, and this basic need would have been compromised by the majority of these wheelchairs as they were not adequately maintained (which relates to the drawbacks of current wheelchair tyre technology). A wheelchair with low wheeling efficiency (inefficient in propulsion from underinflated tyres) can have negative effects on the user including shoulder pain and injury from upper extremity propulsion forces [55]. Elbow, forearm, wrist, and hand pain can also be a result of excessive propulsion. A more recent study on hospital wheelchairs [56] highlights the importance of pneumatic tyre maintenance and the drawbacks associated with improper maintenance. It also states that the typical hospital wheelchair (as of 2004) includes lightweight solid tyres which do not require maintenance but are still not as comfortable as pneumatic tyres. This suggests user comfort is being compromised, and it is likely due to solid tyres being the easier choice financially, whether it be the initial cost of the tyres, or employing someone to regularly maintain (and sometimes replace) them. According to a Research Institute for Consumer Affairs study [57] involving a survey on powered wheelchair users, 34% of respondents use the NHS wheelchair service for wheelchair maintenance, 32% use an equipment supply company (third party company that supply wheelchairs from the manufacturer), 20% use a local shop, and 14% carry out the maintenance themselves. This maintenance involves checking the wheelchair frame, tyres, brakes, seat, armrests, footrests etc. to ensure correct operation. According to the study, only approximately half of users were satisfied with the NHS wheelchair service, and the highest satisfaction at 73% was by users doing the maintenance themselves. This highlights the ongoing need of wheelchair maintenance including checking pneumatic tyres for correct inflation pressure and for any punctures, and also highlights the dissatisfaction of users, which could be improved/overcome through improving wheelchair services and/or reducing required maintenance. Furthermore, improper maintenance can lead to breakdowns which is not only an inconvenience to the user (missing work/school or medical appointments) but has also been associated with higher levels of pain and higher odds of rehospitalisation [58] (although this can depend on the users' medical background such as whether they are ambulatory).

Wheelchair user needs can depend on the location and surrounding environment. Williams et al (2017) explored wheelchair users in less economically developed countries (Kenya and Philippines) and particularly explored if WHO (World Health Organisation) guidelines were being followed [59]. They found that most people had received wheelchairs for free, but with only a few different types of wheelchairs being offered, and some not getting what they requested. In addition, tyres were a source of frustration, and users expressed preference for either inflatable or solid rubber tires. They concluded that free wheelchairs that fit users and providing proper training in usage is limited in poorer countries and should be improved.

Sufficient information is present in literature on wheelchair user needs in general. Literature findings show that for a user to be satisfied and have their needs met, the main characteristics they require from a wheelchair is for it to be safe, comfortable, durable, manoeuvrable, suited to the environment, maintainable, stable, and affordable. . Whilst these needs are common across the wheelchair population, meeting the needs of individual users can depend on the individuals’ physical and mental abilities, as well as their anthropometric measurements, age, gender etc., and there is not a ‘one size fits all’. Whilst there is a significant amount of literature regarding wheelchairs as a whole, there is an absence of literature concerned with wheelchair users’ views and experiences regarding their tyres. Several studies have shown issues with current wheelchair tyre technology (as part of a larger study), but there is a scarcity of literature concerned with the characteristics that user’s desire from their tyres, and there is no evidence of new technology being employed to address these issues. Whether the type of wheelchair influences these tyre characteristics has also remained unexplored. A questionnaire was chosen as a method to address these gaps in literature.

3.2 Methods

3.2.1 Questionnaire Structure

A questionnaire was designed on Microsoft Forms (full questionnaire included in Appendix A). The questionnaire was titled “Wheelchair User Questionnaire”, and its aim was to discover the views and experiences of wheelchair users. The questionnaire sought information about the participants to understand background, environment, and mobility levels, which could influence participants’ needs. More specifically, the questionnaire set out to discover wheelchair users’ experience with conventional tyre technology and their views on ideal tyre technology, and how wheelchair type can influence this. The feedback from respondents should allow interpretation of their specific needs based on wheelchair type and tyre characteristics, which can also inform whether current technology is up to standard in meeting users’ needs.

The criteria for participants were:

- To be a wheelchair user (including ambulatory wheelchair users) using any type of wheelchair.
- To live in the UK.
- To be at least 18 years of age.

The questionnaire was structured with the following sections:

- Information Sheet.
- Consent Form (Q1 - Q8).
- Questionnaire Section 1: Information about you (Q9 - Q14).
- Questionnaire Section 2: Your Wheelchair (Q15 - Q29).
- Questionnaire Section 3: Your Mobility (Q30 - Q33).
- Questionnaire Section 4: Your Wheelchair Tyres (Q34 - Q46).

The information sheet was attached at the beginning of the questionnaire which detailed all aspects of the questionnaire including its purpose, information on taking part, participant anonymity and more. Participants were to read this section in full before moving on to the consent form. Participants had to answer ‘Yes’ to all questions in the consent form before accessing the main body of the questionnaire.

Section 1 of the questionnaire contained questions about the participants age, gender, weight, and the type of environment where they live. This information was required to give a general overview of the demographic characteristics of the responders. The first digits of their post code were also requested to explore the geographical distribution of responders across the UK. Section 2 included questions about the participants wheelchair(s) as a whole, specifically what wheelchair they use, their experience with wheelchairs, if they have made any adjustments, and features they consider most important. Section 3 had questions relating to participants mobility; specifically, how active they are. Mobility and activity levels will likely influence the type of wheelchair and the type of tyres that a user needs in order to suit their requirements. Section 4 contained specific questions about wheelchair users' experiences regarding their tyres. This includes tyre pressure maintenance, punctures, and performance characteristics.

The majority of the questions were multiple choice to reduce the time needed to complete the questionnaire. However, a small number of open questions were deemed necessary to enable responders to include any information they desire at the end of each section. Every question required an answer, but the options 'N/a' and 'prefer not to say' were included in questions where necessary.

3.2.2 Validation and Recruitment

Face validity is a method of ensuring a questionnaire is valid through feedback of experts in the relevant field. A valid questionnaire must have questions all of which are:

- Relevant to the assessment criteria.
- Appropriate for capturing the required data.
- Not harmful to the participants.
- Not anchored/biased to persuade participants.

Relevance and appropriateness can best be determined by experts, whereas potential harmfulness and bias (if any) should be realised during ethical review stages. The questionnaire was validated from the feedback of eight experts. This number of experts was considered appropriate according to literature [60]. Relevant experts consisted of long-term wheelchair users with more than 5 years of experience, UK based manufacturers of bespoke wheelchairs (who work with wheelchair users to design a wheelchair that suits them), and experts in qualitative data and questionnaire fabrication.

After validation, a pilot questionnaire was distributed to a small number of participants (five in total) from the target audience in order to receive additional feedback.

The questionnaire required a full ethical review due to the inclusion of vulnerable adults participating in the questionnaire. This was obtained prior to the collection of any data (SU_21_059). Recruitment of wheelchair users was conducted via the following methods:

- Contacts through family, friends, and colleagues.
- Wheelchair user associated charities.
- Wheelchair sport clubs such as wheelchair basketball (namely Stoke Spitfires).
- A press release detailing information of the study.
- Posting in relevant online forums.
- Contacting wheelchair activists and influencers.

The questionnaire was fully anonymous so it cannot be directly determined where the responses originated from.

3.3 Results

The questionnaire was completed by 117 wheelchair users.

The purpose of the questionnaire was to discover the views and experiences of wheelchair users to interpret their needs and requirements based on current/ideal tyre characteristics combined with the type of wheelchair that they use. Questions about their thoughts and experiences with sections specifically focused on them, their mobility, their wheelchair, and their tyres are subsequently presented in numerous graphs and charts. Each graph/chart is labelled with the respective question number in the questionnaire and is abbreviated to the letter 'Q'. Questions 1 to 8 were part of the consent form. Further question numbers that are not shown (questions 27, 28, 29, 33, and 46) were open-ended questions with an array of responses and were not tabulated here.

In Figure 3.1, Q9 illustrated that the majority of participants were aged between 20 and 49, and the total age range was between 18-19 and 60-69 years. The findings of Q10 showed that a high percentage of the participants (75%) were female, 17% were male, and 8% were non-binary. The most common weight category for users was 70-79 kilograms which is shown in Q11, the weight range of participants was from '40-49' to '150-159' kilograms, and a quarter of participants did not disclose their weight. In terms of accessibility, Q12 showed that the majority of users considered their area to be moderately accessible, while almost a third considered their area to have very limited accessibility. Q13 showed the majority of participants (75%) lived in either a city or town, only 5% lived in the countryside, and the remaining lived in a village.

In Figure 3.2, Q14 showed that 7 participants were from Scotland, 2 from Northern Ireland, at least 4 were from Wales (some postal codes cross over the border), and the remaining (≈100) from England. The Midlands, Northwest, and London area had slightly higher responder numbers, but there is a good distribution of participants all across England and the UK.

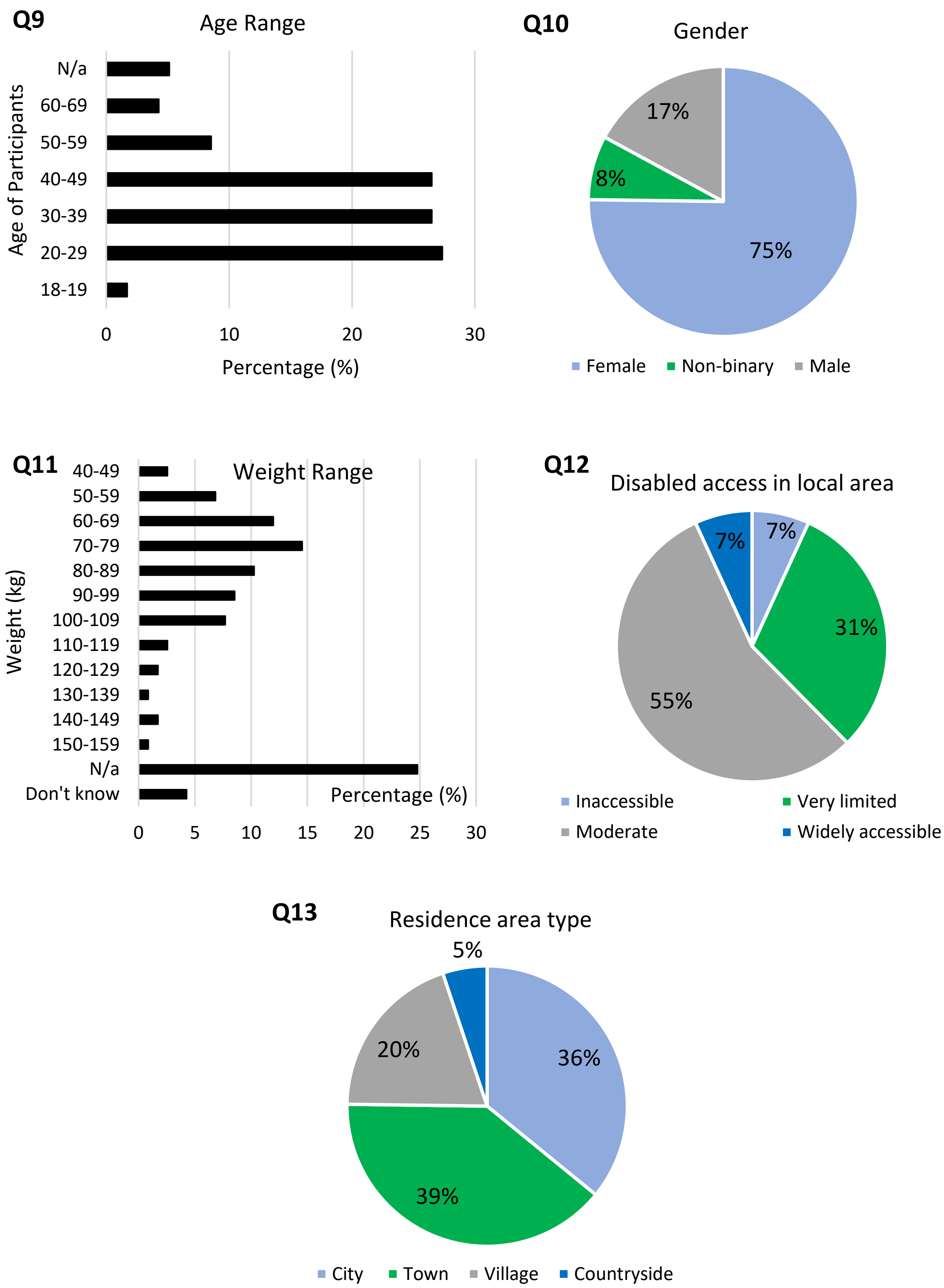


Figure 3.1 - Results from questionnaire section 1: Information about you. Q9: Graph showing the age range of participants. Q10: Chart showing the percentage of gender of participants. Q11: Graph showing the percentage of participants that fall into specific weight ranges. Q12: Chart showing how users rated the level of accessibility in their local area by percent. Q13: Chart showing the type of area that participants live in.

Q14

Figure 3.2 – Results from questionnaire section 1: Information about you. Q14: A map of the UK showing sections divided by postal code area (first one or two characters). The numerical values represent the number of participants in that specific area which participated in the questionnaire. The rectangular section shows a zoomed section of the London area. 3 participants answered N/a (blank district represents zero participants).

In Figure 3.3, Q15 showed that the majority of participants had between 1 to 10 years' experience using a wheelchair, and more than 15% had been using a wheelchair for more than 25 years. Less than 4% had been using a wheelchair for less than 1 year. Q16 showed that the three most common medical conditions for using a wheelchair were spinal injury, Ehlers-Danlos Syndrome, and cerebral palsy. Several other medical conditions were mentioned but categorised into the "other" category due to their combined small percentages (<4% each combining to almost 40%). Q17 showed that approximately half of participants had a custom wheelchair. Q18 showed that only 40% of participants had adjusted their wheelchair seat, and more than half of these adjustments were made to the seat cushion, shown in Q19. Q20 showed that approximately a quarter of participants had adjusted the backrest of their wheelchair.

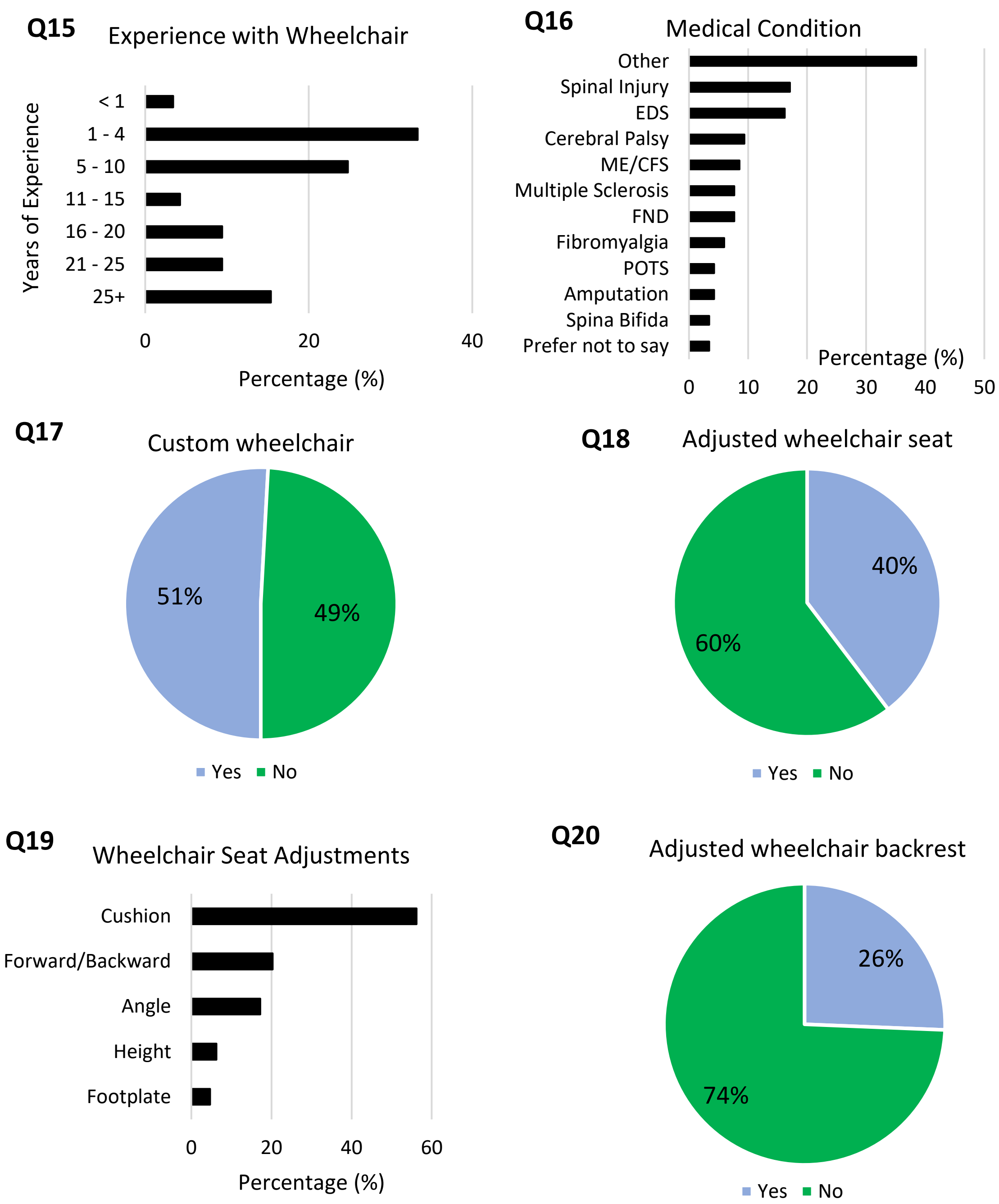


Figure 3.3 – Results from questionnaire section 2: Your wheelchair. Q15: Graph showing the experience of participants in using a wheelchair in years. Q16: Graph showing participants' reason(s) for using a wheelchair (EDS - Ehlers-Danlos syndrome, ME/CFS - Myalgic Encephalomyelitis / Chronic Fatigue Syndrome, FND - Functional Neurological Disorder, POTS - Postural Tachycardia Syndrome). Q17: Chart showing the percentage of participants who own a custom wheelchair. Q18: Chart showing the percentage of participants who have adjusted their wheelchair seat. Q19: Graph showing the specific adjustments that participants have made to their seat. Q20: Chart showing the percentage of participants who have adjusted their backrest.

In Figure 3.4, Q21 showed that almost half of users that had adjusted their backrest had adjusted the angle, and the remaining had either moved it forwards/backwards or altered the height. Q22 showed that 62% of participants were manual wheelchair users, 29% were electric wheelchair users, and 9% used both types of wheelchairs. Q23 showed that 30% of participants had experience using both a manual and an electric wheelchair for at least 3 months each. Q24 showed that approximately two-thirds of participants preferred electric wheelchairs, approximately a quarter preferred manual wheelchairs, and 6% had no preference. Q25a demonstrated that 'less exertion' is the main reason for those who prefer an electric wheelchair (over 40%), with comfort and manoeuvrability being the second and third reasons respectively. Q25b showed that manoeuvrability is the main reason why participants prefer a manual wheelchair (said by half of the participants), and comfort (≈30%) and low maintenance (≈20%) being the other two reasons. Q26 showed that almost three quarters of the participants stated that their needs differ depending on the wheelchair type (manual/electric), 6% believed them to be the same, and 20% were unsure.

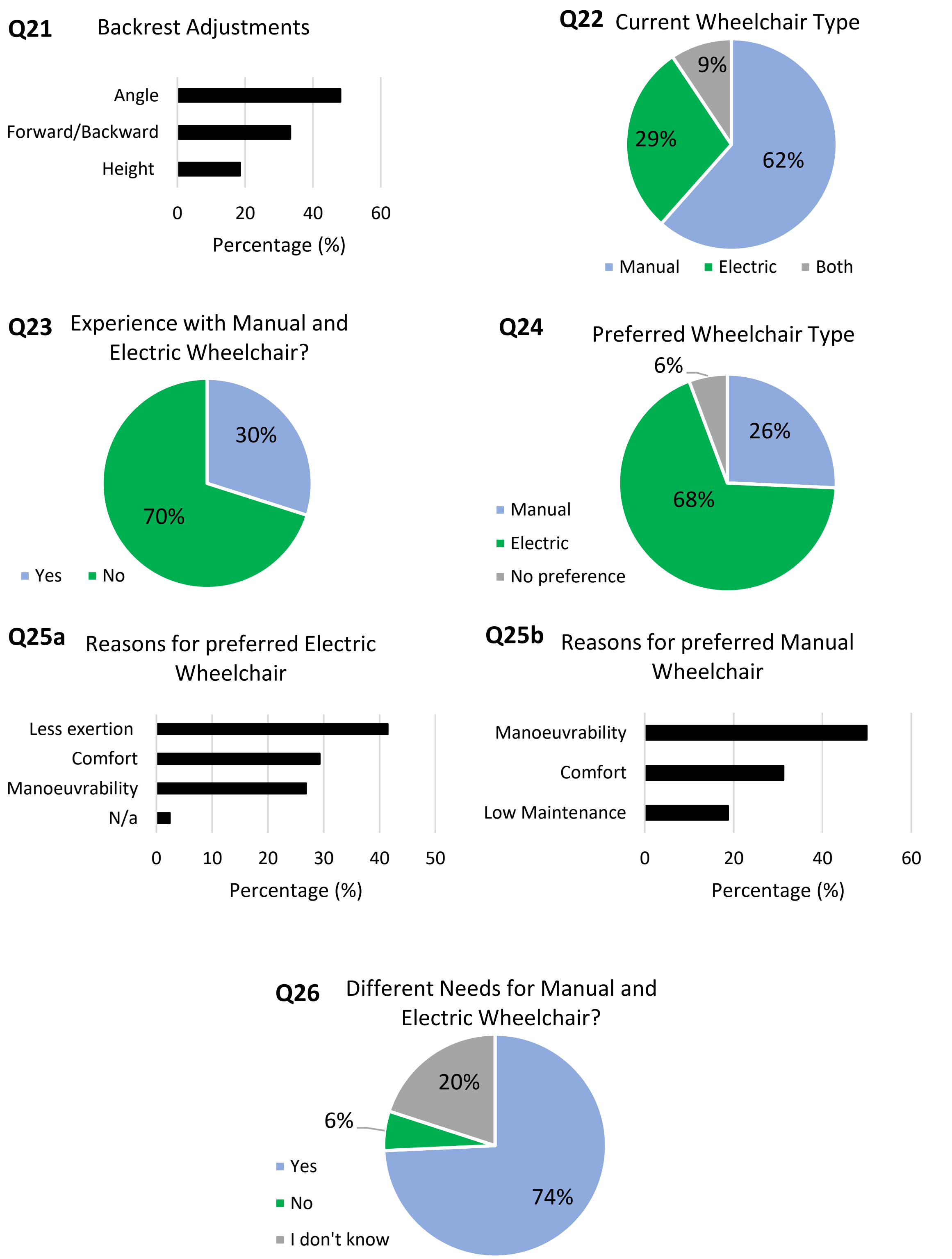


Figure 3.4 – Results from questionnaire section 2: Your wheelchair. Q21: Graph showing the adjustments that users have made to their backrest. Q22: Chart showing the type of wheelchair that users currently use. Q23: Chart showing the percentage of participants that have experience using both a manual and an electric wheelchair for at least 3 months each. Q24: Chart showing preferred wheelchair for participants who have experience using both. Q25a: Graph showing the reasons why participants preferred electric wheelchairs. Q25b: Graph showing the reasons why participants preferred manual wheelchairs. Q26: Chart showing the percentage of participants that feel their needs are different for manual and electric wheelchairs.

In Figure 3.5, Q30 showed that most participants did not engage in any physically intense activities per week, and less than 5% did 5 hours or more per week. Q31 showed that 5% of participants usually stayed at home every day, and the majority of participants spent 4 to 6 days at home. Q32 showed that two thirds of participants can stand up and move to some degree without their wheelchair.

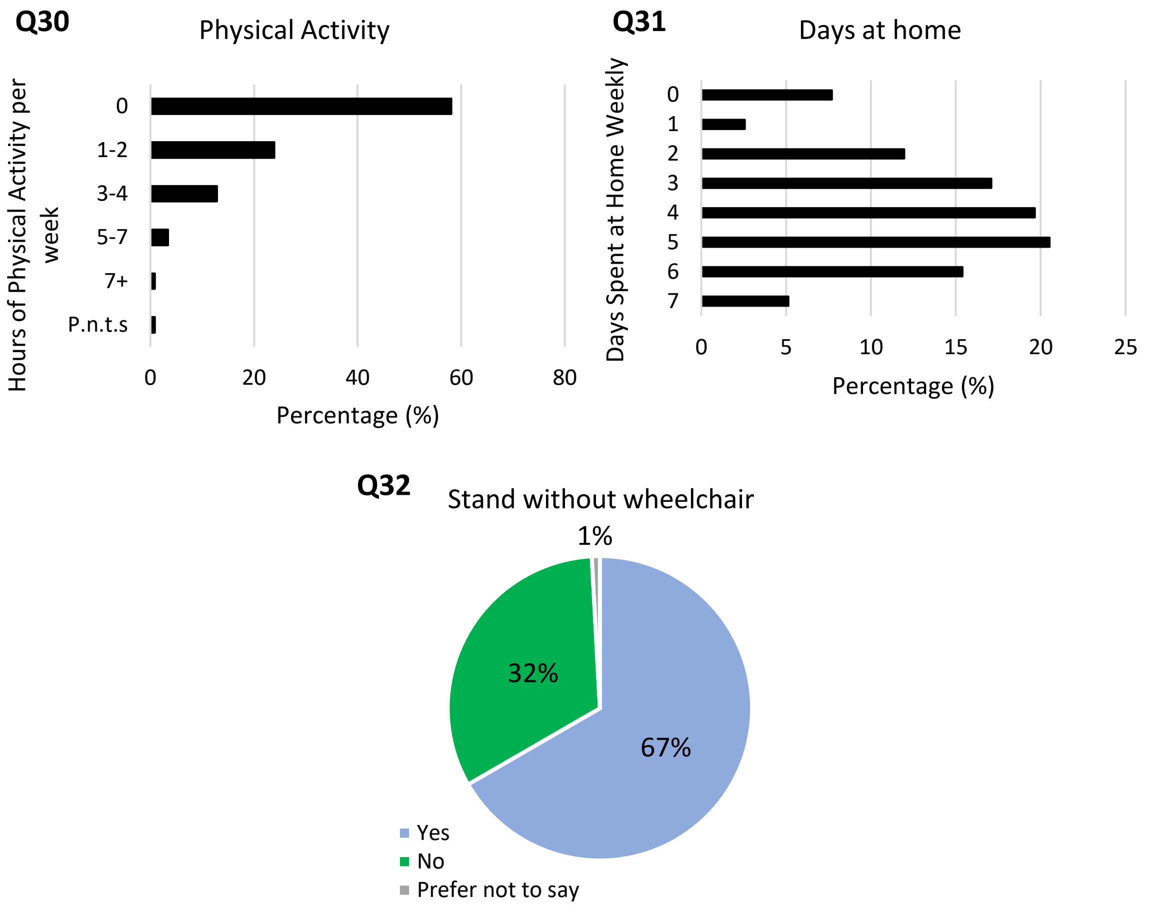
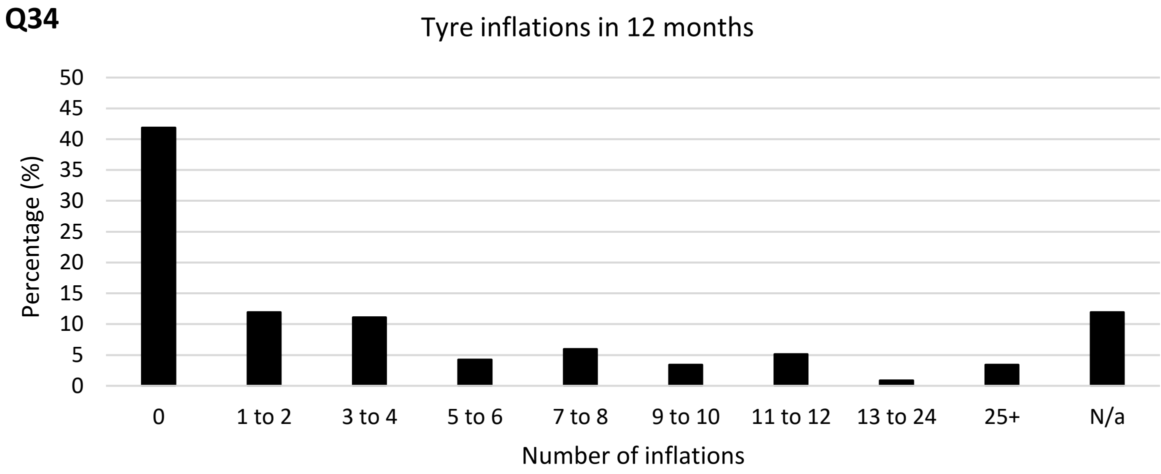
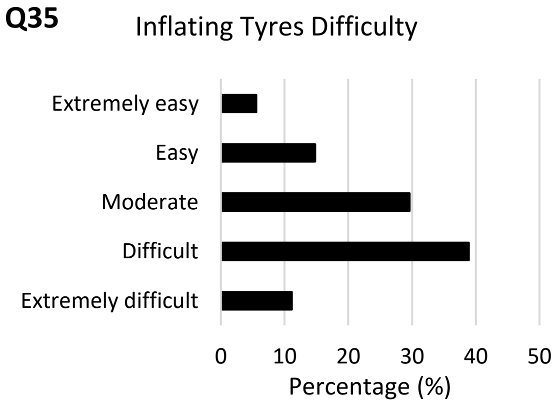


Figure 3.5 - Results from questionnaire section 3: Your mobility. Q30: Graph showing participants' hours of physical activity per week (p.n.t.s stands for prefer not to say). Q31: Graph showing the number of days that participants spend at home in a typical week. Q32: Chart showing the percentage of participants that can stand without their wheelchair.

In Figure 3.6, Q34 showed that over 40% of participants did not inflate their tyres at all, ≈23% had 1 to 4 inflations, and a small number of participants (≈3%) inflated their tyres more than 24 times in the previous 12 months (from when it was answered). Q35 showed that the most common result for the rated level of difficulty regarding tyre inflation was 'difficult'. Almost all users inflated their tyres from home according to the findings of Q36.





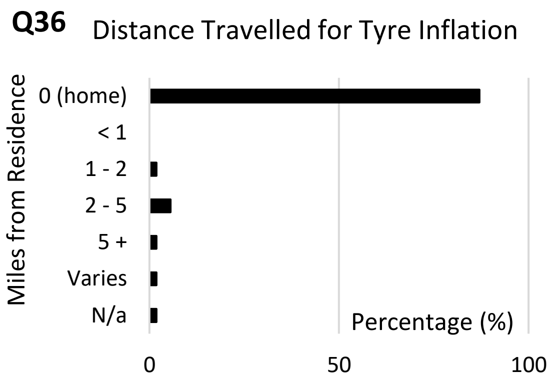


Figure 3.6 - Results from questionnaire section 4: Your wheelchair tyres. Q34: Graph showing the number of times that participants inflated their tyres in the last 12 months. Q35: Graph showing the participant rated difficulty level of tyre inflation. Q36: Graph showing the distance users travel to inflate their tyres in miles.

In Figure 3.7, more than 70% of participants did not have any tyre punctures according to Q37, and ≈17% had between 1 and 4 punctures in the last 12 months. 'Extremely difficult' was the most common choice relating to the level of difficulty for repairing or replacing tyres according to participants answers for Q38, and this difficulty category was chosen twice as much compared to any other level of difficulty. Q39 showed that almost 40% of participants repaired or replaced their punctured tyres at home, and almost 40% usually travelled between 1 to 5 miles to achieve this.

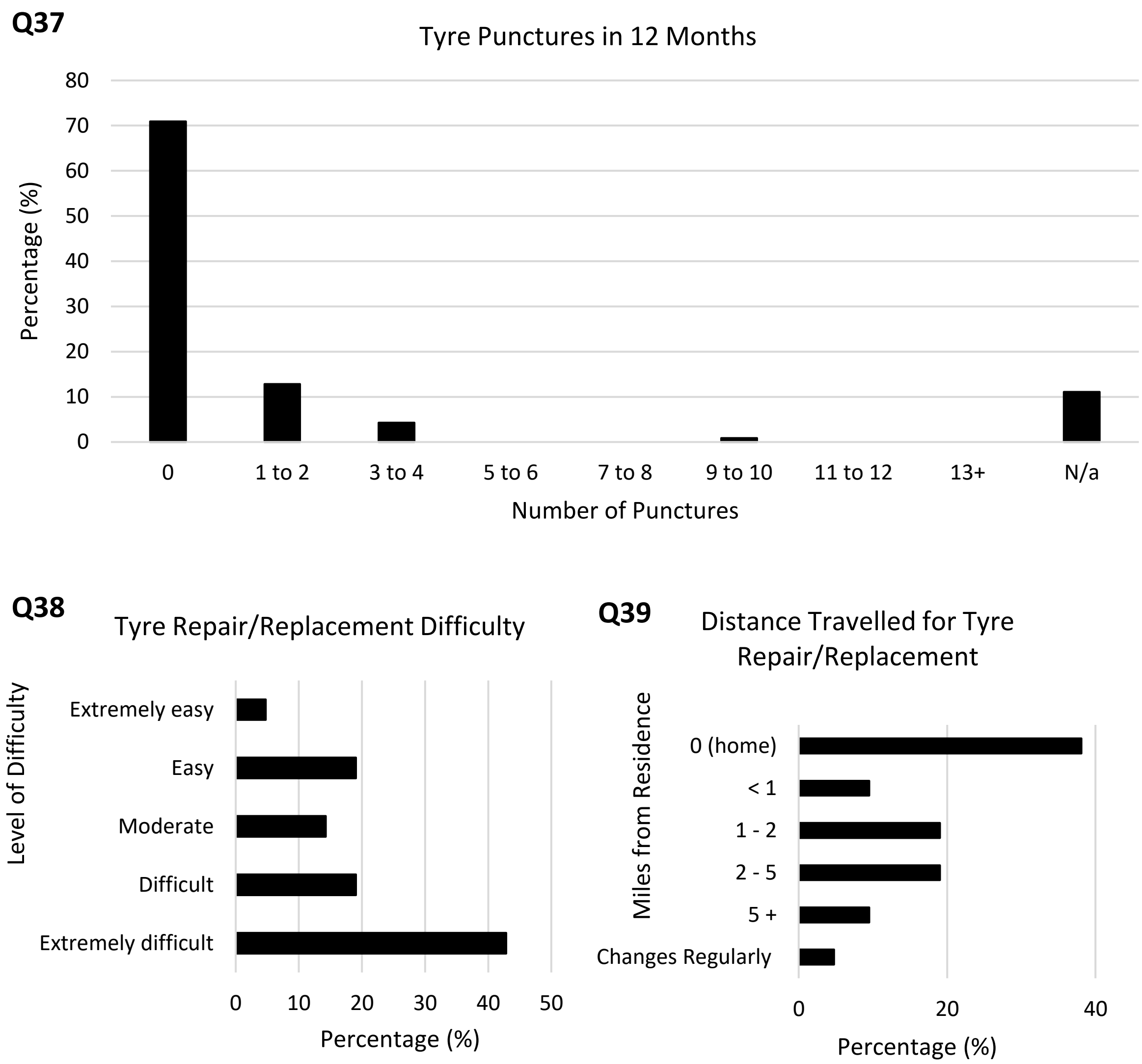
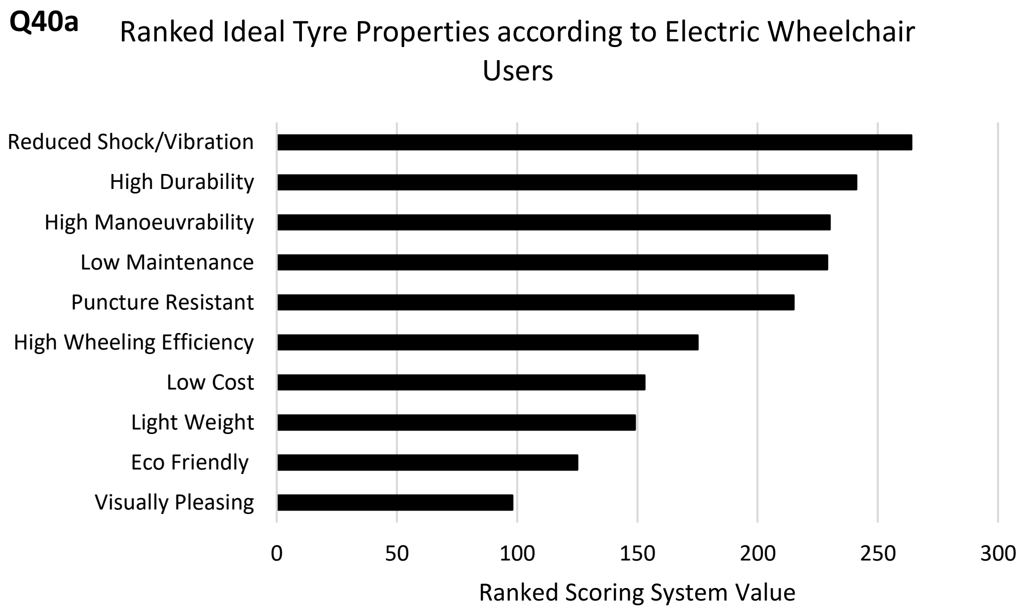


Figure 3.7 - Results from questionnaire section 4: Your wheelchair tyres. Q37: Graph showing the number of times that participants experienced a tyre puncture in the last 12 months. Q38: Graph showing the participant rated difficulty level of tyre repair or replacement. Q39: Graph showing the distance users travel to repair or replace their tyres in miles.

In Figure 3.8, a weighted ranking method was used to assess tyre characteristics (the same method used in Microsoft Forms). A characteristic ranked first would receive 10 points (due to there being 10 characteristics in total), a characteristic ranked second would receive 9 points, and this process continued to the last ranked characteristic receiving 1 point. The results of all participants were combined to give a final value for each characteristic (the scores for manual wheelchair users were higher due to more manual wheelchair user responders in this questionnaire). Q40a showed that electric wheelchair users ranked their top three characteristics for their ideal tyres as reduced shocks/vibrations, high durability, and high manoeuvrability.

The lowest ranked characteristic was visually pleasing tyres, followed by eco-friendly and light-weight. For manual wheelchair users, Q40b shows that the top three characteristics were high wheeling efficiency, reduced shock/vibration, and light weight. The lowest ranked were visually pleasing, eco-friendly, and low cost.



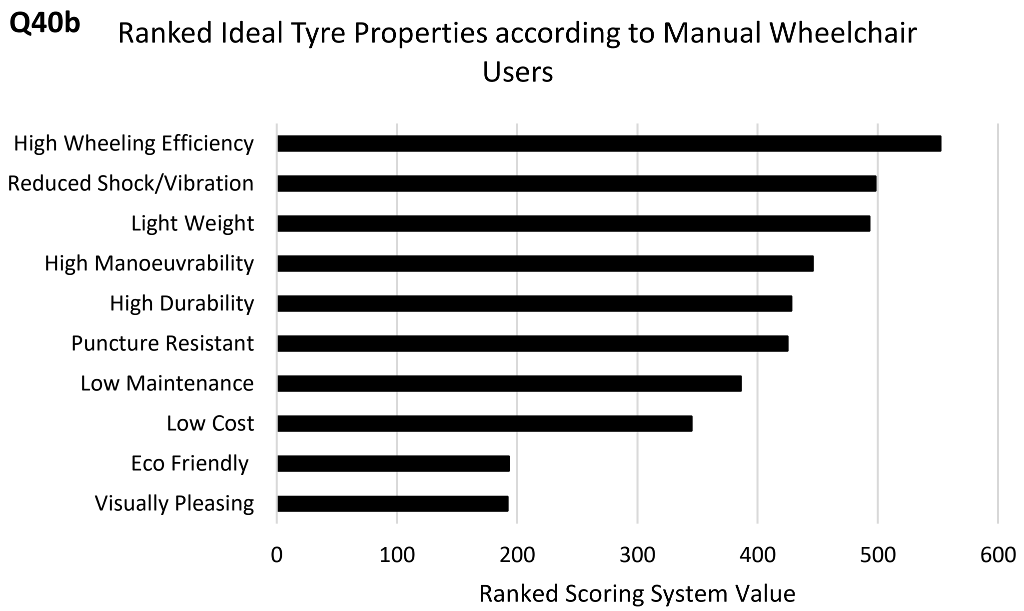
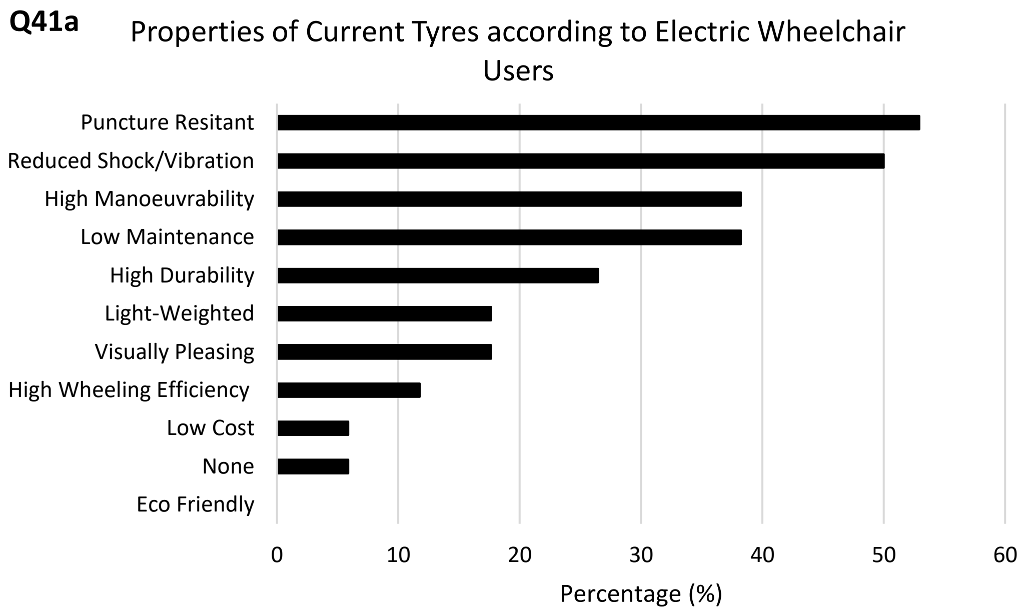


Figure 3.8 - Results from questionnaire section 4: Your wheelchair tyres. Q40a: Graph showing ranked tyre characteristics that electric wheelchair users would like their ideal wheelchair tyres to have (the ranked scoring system is calculated based on the position and occurrence of characteristics). Q40b: Graph showing ranked tyre characteristics that manual wheelchair users would like their ideal wheelchair tyres to have.

In Figure 3.9, Q41a showed that most electric wheelchair users had puncture resistant tyres, half of users had tyres with shock/vibration absorbing properties, and over a third had tyres that had high manoeuvrability and were low maintenance. ≈6% stated that their tyres did not have any of the properties stated in the previous question. According to manual wheelchair users, Q41b showed that just over a third of participants had puncture resistant tyres, and approximately a quarter had light weight and low maintenance tyres. ≈7% had shock/vibration absorbing tyres and ≈12% stated that their tyres did not have any of the aforementioned characteristics.



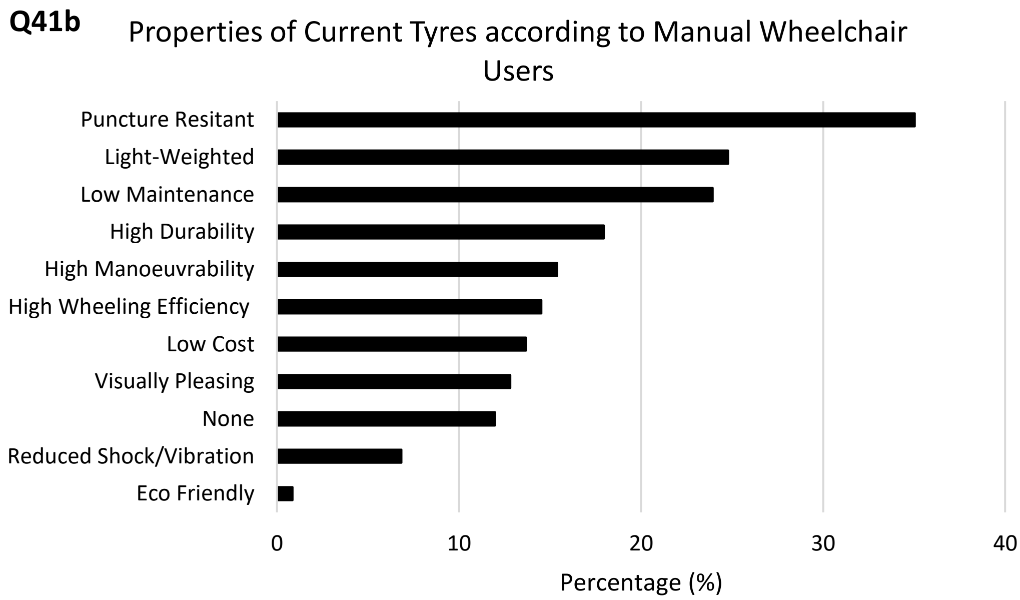


Figure 3.9 - Results from questionnaire section 4: Your wheelchair tyres. Q41a: Graph showing the actual tyre properties that electric wheelchair users currently have. Q41b: Graph showing the actual tyre properties that manual wheelchair users currently have.

In Figure 3.10, almost a third of participants preferred their tyre inflation pressure to be at manufacturer's recommended according to Q42, ≈9% prefer it to be higher, and <1% prefer it to be lower. Approximately a quarter of users selected 'N/a'. Q43 showed that 'difficult' was the most commonly chosen option regarding maintaining their preferred tyre pressure. Q44 showed that more than three quarters of participants noticed a difference in wheelchair performance when their tyres were not at optimal pressure. Q45 showed that ≈40% did not know if their tyres could provide the highest level of comfort and propulsion efficiency simultaneously, and an almost equal amount answered yes/no.

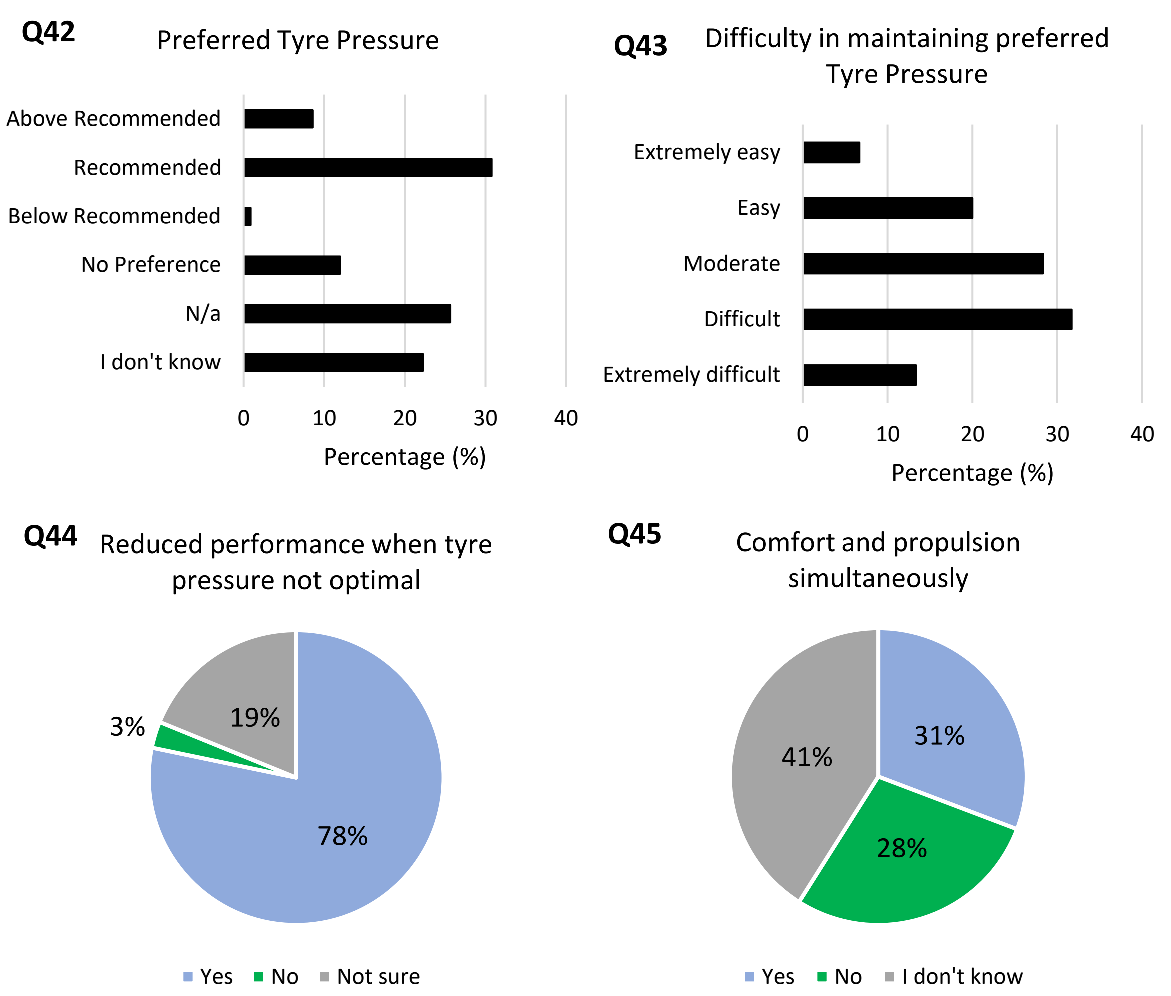


Figure 3.10 - Results from questionnaire section 4: Your wheelchair tyres. Q42: Graph showing users' preferred tyre inflation pressure relative to manufacturers recommended (or pressure displayed on the tyre). Q43: Graph showing the difficulty level associated with users maintaining their preferred tyre pressure. Q44: Chart showing the percentage of participants that have noticed differences in the performance and handling of their wheelchair when their tyre pressure is not optimal. Q45: Chart showing the percentage of participants that feel that their tyres can provide the highest level of comfort and wheeling efficiency simultaneously.

3.4 Discussion

The purpose of the questionnaire was to discover the views and experiences of wheelchair users to interpret their needs. In terms of validity of this questionnaire, research into previous questionnaires with similar target audiences [61,62] was conducted and the average sample size was calculated to be 50 participants. This was deemed the minimum required to be able to make any valid assumptions/arguments. A total of 117 participants completed the questionnaire, which was considered sufficient to draw reliable conclusions.

The main findings of this questionnaire indicate that the perceived needs of manual and electric wheelchair users appear to be different. Electric wheelchair users preferred shock absorbing, durable, and manoeuvrable tyres (in ascending order), whereas manual wheelchair users preferred wheeling efficient, shock absorbing, lightweight tyres. Furthermore, inflating pneumatic tyres and repairing/replacing them were considered difficult and extremely difficult tasks respectively, and puncture resistant tyres were the most commonly used tyre types among both electric and manual wheelchair users.

Tyres with reduced shock/vibration were among the top three ranked characteristics according to both electric and manual wheelchair users (Figure 3.8 – Q40a and Q40b), and 50% of electric wheelchair users stated that their actual tyres had this characteristic, whereas less than 7% of manual wheelchair users had this characteristic (Figure 3.9 – Q41a and Q41b). As participants' ideal tyres would be considered the tyres they require to meet their needs, shock/vibration absorbing tyres is a need of manual wheelchair users that is not being met for the vast majority of users. This tyre characteristic also relates to the comfort of a wheelchair, which was considered an important need of wheelchair users according to literature [1]. This could imply that users are using solid non-pneumatic tyres or incorrectly inflated pneumatic tyres with poor suspension properties.

Wheeling efficiency was not a high-ranking tyre characteristic for electric wheelchair users, but it was the top ranked property for manual wheelchair users. Furthermore, less than 15% of manual wheelchair users stated that their tyres were highly efficient during wheeling (Figure 3.8 – Q41b). As this characteristic greatly determines the ease of moving the wheelchair, this is another important need of wheelchair users that is potentially being compromised due to their tyres [1]. It is important to consider here that there could be different perceptions among respondents as to what the term 'high' in high wheeling efficiency actually means, and it is also a characteristic that can be difficult to quantify. It is assumed that participants will have associated high wheeling efficiency with ease of propulsion, and so if they have experienced improved performance in the past, or they have associated propulsion injuries, then it is fair to infer that they would assume that their tyres are not of high wheeling efficiency (and their assumption would likely be valid). Manual wheelchair users also ranked light weight tyres as the third highest desirable characteristic, but less than 25% claimed they had lightweight tyres. Marchiori et al (2015) asked wheelchair users to rate wheelchair aspects and found that users were not satisfied with outdoor propulsion or the weight of the wheelchair which is in some agreement with the findings of this questionnaire. Wheeling efficiency and light-weight are two tyre characteristics of which FS-NPTs are suggested to be able to provide enhanced behaviour over current tyre technology. As these properties (as well as reduced shocks/vibrations) are most important to manual wheelchair users, this suggests that FS-NPTs would be most beneficial to them. As the tyre types for manual and electric wheelchairs have previously been defined and shown to be largely different in dimensions and loading capacity, the design of an FS-NPT would also be largely different for each wheelchair type and will therefore require thorough individual investigations. It is therefore reasonable to suggest that producing an FS-NPT for a manual wheelchair would be most beneficial for its users (specifically standard/active with push rim attached for user self-propulsion).

Figure 3.10 – Q44 showed that for those who were applicable, 78% agreed that a sub-optimal tyre pressure impacts the performance and handling of the wheelchair. This is in agreement with literature which found reduced performance with reduced tyre pressure [6]. This implies that pneumatic tyres with incorrect inflation pressure causes user needs to be compromised as they are not providing the necessary characteristics to propel the wheelchair comfortably, safely, with ease, and mitigating the potential for injury. Furthermore, the majority found it 'difficult' to inflate their tyres and to maintain their tyre pressure (Figure 3.6 – Q35 and Figure 3.10

– Q43), which emphasises how the disadvantage of current tyre technology (maintaining pressure) negatively impacts users' needs.

Regarding tyre punctures, 18% of participants had at least one puncture in the previous 12 months (Figure 3.7 – Q37) which is similar to Withrington et al as they found that 17% of hospital wheelchairs had punctures [54]. A puncture usually results in complete failure of the tyre which causes inconvenience and will require purchasing a new tyre in most cases. 62% found it either difficult or extremely difficult to repair/replace a punctured tyre (Figure 3.7 – Q38), highlighting an extreme drawback of pneumatic tyres and why many people use solid non-pneumatic tyres with less absorption abilities.

3.4.1 Limitations

There were some limitations of this study which may have influenced the results of the questionnaire. One such limitation was that the cohort of participants was not gender balanced (Figure 3.1 - Q10). Although according to Marchiori et al (2015), age and gender do not have an impact on results when compared with global satisfaction scores [50].

Another limitation is that the user needs have been defined solely through a questionnaire of which most questions were multiple choice. This could limit the response that participants wanted to give, and written questions can sometimes be misinterpreted. This study however can act as a foundation and can guide the design of future interview-based work for a more in-depth view into wheelchair user needs.

3.5 Conclusion

The purpose of this questionnaire was to explore the views and experiences of wheelchair users. This information was key in interpreting the specific needs of wheelchair users and providing insight as to whether these needs are being (or can be) met by current technology. The main findings were:

- The needs of manual and electric wheelchair users are different.
- Users found it difficult or extremely difficult to maintain their tyre pressure or repair/replace their tyre respectively, highlighting the drawbacks of current wheelchair tyre technology.
- In order of importance, manual wheelchair users rank wheeling efficiency, shock/vibration absorption, and light-in-weight as the top three most desirable tyre characteristics.
- High durability and high manoeuvrability are among the desirable tyre characteristics for manual and electric wheelchair users.
- Manual wheelchair tyres are unable to provide desired characteristics (specifically high durability and high manoeuvrability) according to most users.
- The advantages that FS-NPTs can potentially offer would be most beneficial for manual wheelchair users according to their responses on their ideal tyre characteristics.

Overall, the questionnaire provides insight into wheelchair user needs, specifically regarding their tyres, which is information that was not available in literature. This study addresses this gap, providing details of user experience with current tyre technology, and what their ideal tyres should have, which can inform the design of new tyre technology to meet the needs of wheelchair users. The findings of this questionnaire were drawn from the cohort of participants involved; characterising the complex needs of an individual requires more in-depth investigations.

The tyre characteristics that users have stated that they need from this assessment of wheelchair user needs can be translated into mechanical properties. Wheeling efficiency and comfort are closely tied to the shear and vertical stiffness of a tyre respectively. To design a manual wheelchair FS-NPT that can outperform current technology, baseline characteristics of this technology is required for comparison. More specifically, the significant mechanical properties related to the questionnaire findings should be measured, namely vertical stiffness, shear stiffness, and mass.

Chapter 4: Baseline Mechanical Properties of a Manual Wheelchair Pneumatic Tyre

4.1 Introduction

Wheelchair tyres are crucial components of a wheelchair influencing the comfort, wheeling efficiency, manoeuvrability, and overall user experience. As previously mentioned, there are various types of tyres that exist which can tailor to the specific needs of individual wheelchair users, with the main two types being solid non-pneumatic and pneumatic. Pneumatic tyres can provide satisfactory levels of comfort and wheeling efficiency (when maintained correctly) according to literature [63] and thus can contribute towards meeting the needs of wheelchair users, but their drawbacks, namely punctures and maintenance, means solid non-pneumatic are a viable choice. Properly inflated pneumatic tyres are currently the best choice for wheelchair users in meeting their comfort and wheeling efficiency needs.

FS-NPTs were suggested as a technology which can replace conventional tyres by providing high levels of comfort and wheeling efficiency, as well as being puncture proof and maintenance free. To determine if FS-NPTs can firstly replicate, and ultimately offer an improvement to conventional wheelchair tyre technology, thorough assessment of the mechanical behaviour of current tyre technology is needed. Vertical stiffness, shear stiffness, and mass are considered as significant mechanical properties that heavily influence the behaviour of a tyre. The vertical (or radial) stiffness of a tyre is quantified as the vertical force applied divided by the resultant vertical displacement (kN/m). According to literature, the vertical stiffness in general determines user comfort [64]. A tyre with lower vertical stiffness will have higher suspension properties than a more rigid tyre, leading to increased dampening of shocks and vibrations to provide a more comfortable wheelchair [6]. However, a significantly low vertical stiffness will result in a tyre unable to support the weight of the vehicle/equipment and thus impeding its functionality, and this stiffness threshold varies for different applications. The shear stiffness is quantified as the moment applied divided by the resultant rotation (Nm/°). According to literature, the shear (or rotational) stiffness of a tyre can influence propulsion efficiency and the tyre's rolling resistance [65,66]. A tyre with high shear stiffness will result in lower energy losses through circumferential deformation and will make it easier for a user to propel. Whilst vertical stiffness can also influence rolling resistance, it is mainly tied to tyre suspension and thus user comfort, whereas shear stiffness almost exclusively influences rolling resistance (and has minimal effect on tyre suspension). Furthermore, the weight of the tyre can also impact user propulsion. A heavy tyre will require more energy to overcome inertia and increase the rolling resistance [67], and in the particular case of wheelchairs, even small increases in tyre weight have noticeable increases on rolling resistance [6]. An increase in tyre weight will also make it more difficult for independent manual wheelchair users to dismantle/assemble and transport their wheelchair when travelling or at home.

The objective of this chapter was to therefore establish baseline characteristics of a wheelchair pneumatic tyre through laboratory testing. The baseline characteristics were required for comparisons with future potential competitive technology (FS-NPTs).

4.2 Methodology

A conventional active wheelchair frame (RGK Hi-Lite) with standard pneumatic tyres attached (Kenda, inflated to a pressure of 80psi / 552 kPa) was used in order to quantify experimentally the tyre's vertical and shear stiffnesses (Figure 4.1). The front wheels (caster wheels) of the wheelchair were removed, and weights were added to the lower frame to ensure the wheelchair would not move or slide during the experiments (Figure 4.3a). The weight of individual components of the tyre was measured using a precision scale.

Figure 4.1 - RGK active wheelchair with Kenda pneumatic tyres (backrest folded down).

4.2.1 Setup

The left wheelchair wheel/tyre (whilst attached to the wheelchair) was placed on a built-in force plate (AMTI OPT464508HF sampling at 1000Hz; AMTI, USA) which measured the ground reaction force of the left tyre/wheel. A displacement gauge (LINEAR, 0.01mm resolution) was placed on the rim of the wheel just above the tyre-ground contact region to measure the vertical displacement of the tyre (Figure 4.2a). A metallic beam was fixed to the rim of the wheel with one end protruding outwards.

A digital goniometer (Digi-Pas DWL-180, ± 0.05° accuracy) was placed at the top of the tyre (on the sidewall) which measured the rotation in degrees (Figure 4.2b).

For the first test, a vertical load was applied via weighted plates placed atop the wheelchair in 25kg increments up to a maximum of 75kg (Figure 4.3a), which was the average weight of a wheelchair user according to literature [68] and the questionnaire (Figure 3.1 – Q11). For the second test, in addition to a 75kg vertical load on the wheelchair, 5kg weights were hung from the beam at varied lengths to apply moment magnitudes in 5Nm increments up to a maximum of 25Nm. This maximum moment magnitude is the average value for a user's initial wheeling stroke on level concrete [69] (Figure 4.3b). Both test 1 and test 2 were repeated to ensure consistent results were obtainable and the tests were repeatable. Measurements of the goniometer were also taken during offloading to ensure there was no tyre slippage.

Figure 4.2 – Close up images of tyre measuring aparatus: (a) Displacement gauge. (b) Digital goniometer.

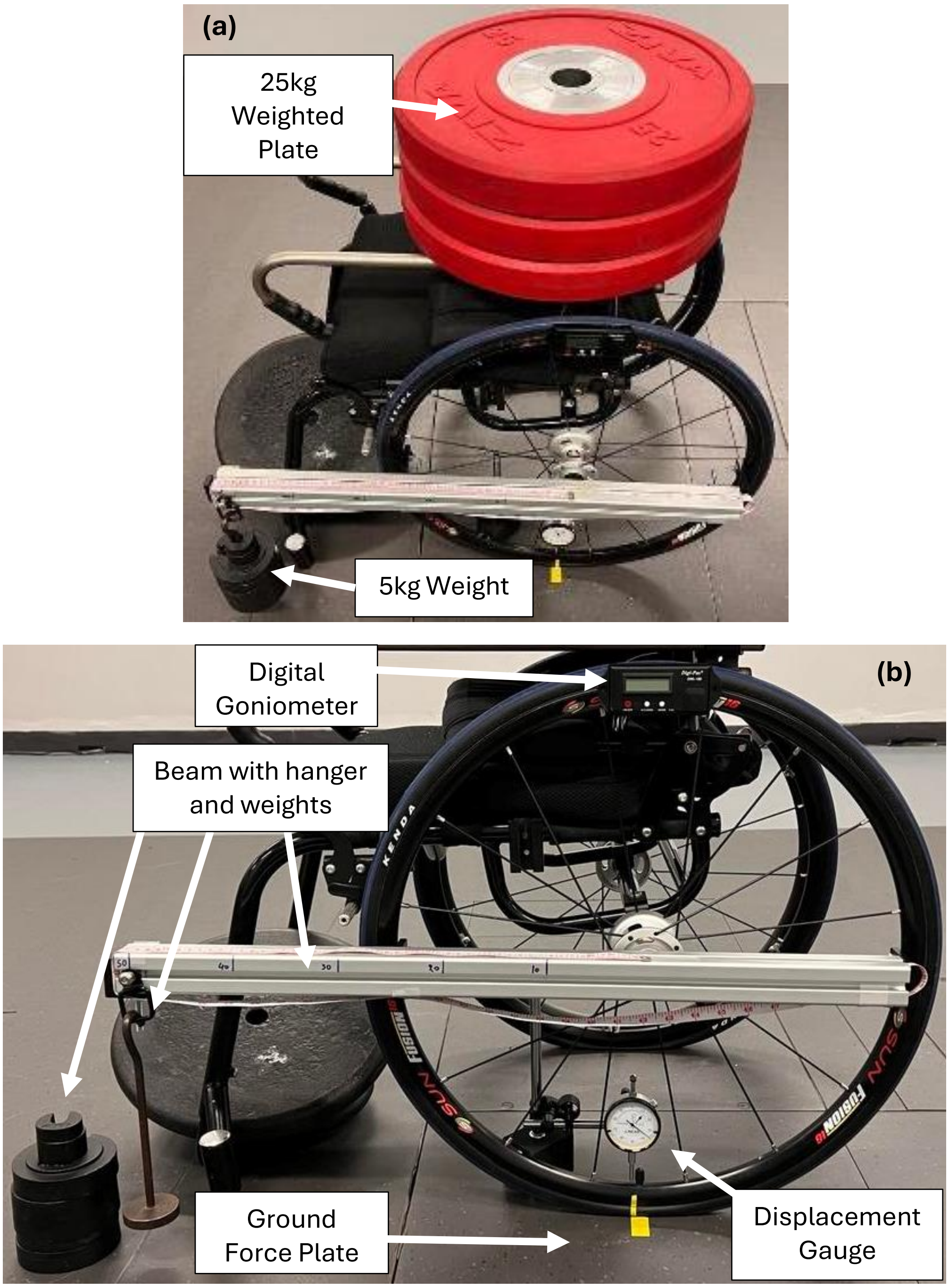


Figure 4.3 - (a) Wheelchair experimental setup. (b) Side view with labels showing displacement gauge for quantifying vertical stiffness (load applied from weighted plates atop the wheelchair), and a digital goniometer for quantifying shear stiffness (load applied from weights attached to the beam).

4.3 Results

The pneumatic tyre weighed 0.300 kg, and the inner tube weighed 0.108 kg, giving a combined total of 0.408 kg for the pneumatic tyre compared to the average weight of 0.488 kg of three different wheelchair pneumatic tyres in literature [6].

Vertical displacement increased linearly with increasing vertical load (Graph 4.1). After calculating the average slope of the results for three tests (Table 4.1), the average vertical stiffness of the reference pneumatic tyre was 138.97 kN/m, and the standard deviation was 7.64 kN/m (Table 4.2).

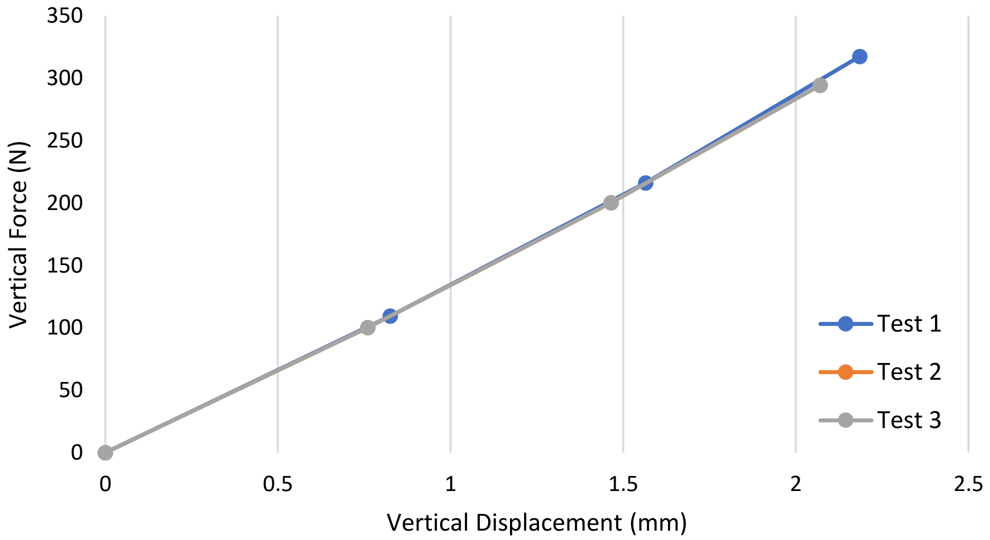
Rotation also increased linearly with increasing applied moments (Graph 4.2). After averaging results for two tests (Table 4.3), the average shear stiffness of the reference pneumatic tyre was 32.41 Nm/° and the standard deviation was 0.18 Nm/° (Table 4.4). There was no relative slipping between the tyre and the ground.

Table 4.1 – Measurements from test 1 (vertical load) of the wheelchair tyre experiment that were used to calculate vertical stiffness.

Test Number	Applied weight (kg)	Reaction Force (N)	Displacement (mm)	Vertical Stiffness (kN/m)
1	0	0	0	0
	25	105.1	0.87	120.80
	50	209.5	1.65	126.97
	75	305.8	2.35	130.13
2	0	0	0	0
	25	109.5	0.825	132.73
	50	216.2	1.565	138.15
	75	317.4	2.185	145.26
3	0	0	0	0
	20	100.2	0.76	131.84
	50	200.1	1.465	136.59
	75	294.3	2.07	142.17

Table 4.2 - Calculated values of vertical stiffness and standard deviation. Average applied load and average displacement of the tyre are shown.

Averaged Vertical Stiffness (kN/m)	Standard Deviation (kN/m) (coefficient of variation)	Average Load (N)	Average Displacement (mm)
138.97	7.64 (5.5%)	305.83	2.2



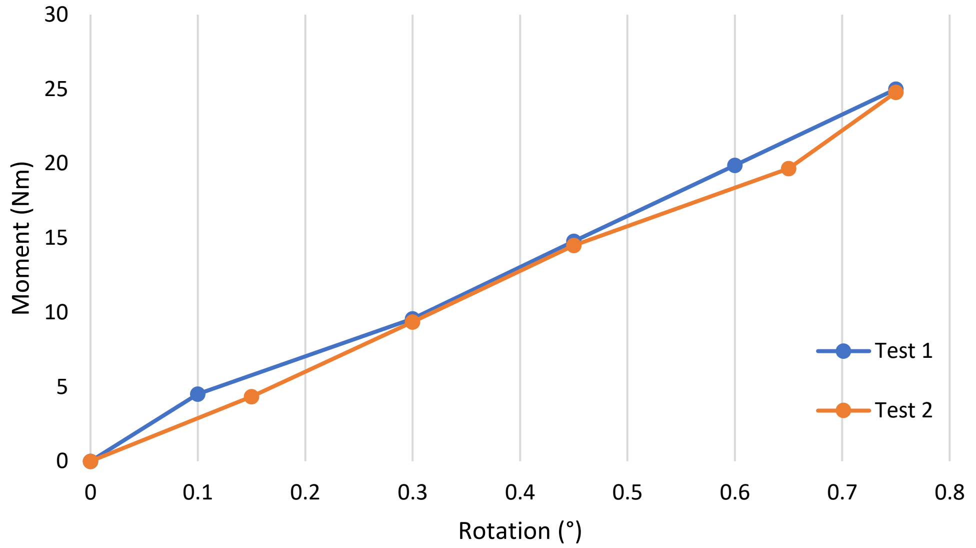
Graph 4.1 - Vertical stiffness of the pneumatic tyre over three test runs.

Table 4.3 – Measurements from test 2 (vertical and shear load) of the wheelchair tyre experiment that were used to calculate shear stiffness.

Test Number	Theoretical Moment (Nm)	Shear Magnitude [Fx and Fy] (N)	Actual Moment (Shear Magnitude x Tyre Radius) (Nm)	Resultant Rotation (°)	Shear Stiffness (Nm/°)
1	0	0	0	0	0
	5	14.80	4.51	0.1	45.15
	10	31.39	9.57	0.3	31.91
	15	48.46	14.78	0.45	32.84
	20	65.17	19.88	0.6	33.13
	25	81.96	25.00	0.75	33.33
2	0	0	0	0	0
	5	14.26	4.35	0.15	28.99
	10	30.67	9.36	0.3	31.19
	15	47.53	14.50	0.45	32.21
	20	64.47	19.66	0.65	30.25
	25	81.27	24.79	0.75	33.05

Table 4.4 - Calculated values of shear stiffness and standard deviation. Average applied moment and average rotation of the tyre are shown.

Averaged Shear Stiffness (Nm/°)	Standard Deviation (Nm/°) (coefficient of variation)	Average Moment (Nm)	Average Rotation (°)
32.41	0.18 (0.6%)	24.9	0.75



Graph 4.2 - Shear stiffness of the pneumatic tyre over two test runs.

4.4 Discussion

The purpose of this experiment was to measure the vertical stiffness, shear stiffness, and mass of a standard pneumatic tyre to acquire the baseline measurements for comparisons with FS-NPTs in subsequent chapters.

Previous studies in literature have focused on testing wheelchair and bicycle pneumatic tyres (which have very similar dimensions to wheelchair tyres). These tests however were normally dynamic and focused on tyre cornering and aligning abilities [70,71] and difficult to directly compare with this static test setup. The vertical stiffness of bicycle pneumatic tyres was measured by Rothhammel at different internal pressures [72], however, they only tested up to a pressure of 300 kPa (compared to 552 kPa in this study) at which the vertical stiffness of these tyres was on average 99 kN/m (compared to 139 kN/m in this study). Gordon calculated the spring constant of a wheelchair pneumatic tyre based on the slope of the load-deflection curve (which is defined in this and other studies as the vertical stiffness) and found an average vertical stiffness value of 118 kN/m (converted from lb/in) [63]. This tyre was the same size to the one used in this study (24”), but the internal pressure was 60 psi (compared to 80 psi in this study) which explains the slightly higher vertical stiffness measured here.

Shear stiffness has been quantified for an FS-NPT in previous work with an average value of 84 Nm/° [73], compared to the measured value of 32 Nm/° for the pneumatic tyre. This could be an initial insight into a potential benefit that FS-NPTs could offer (as a higher shear stiffness means less energy loss during propulsion). Tyre shear stiffness directly influences tyre rolling resistance, which has been measured for pneumatic tyres at varied internal pressures in literature [6,39]. As previously mentioned, vertical stiffness can also influence rolling resistance but is more importantly a measure of tyre suspension ability.

4.4.1 Limitations

There were limitations of this study which could have impacted the results. One such limitation was that a small number of repeat tests were done for quantifying vertical and shear stiffness. However, the small standard deviations and coefficients of variation indicate that the independent tests were in close agreement with each other and should therefore be accurate.

Due to the applied weights being manually applied (rather than a motorised system such as a load frame), the tests were limited to static loading. The static analyses in this study provide insight into baseline mechanical behaviour and is an important starting point before moving to the study of dynamic loading conditions. Dynamic simulations should be conducted in the future to illustrate the behaviour of the tyre during propulsion, and this would allow for assessment of other tyre characteristics such as manoeuvrability and durability which were important according to wheelchair user input from the questionnaire, but a more advanced setup is required.

4.5 Conclusion

The aim of this experiment was to measure the vertical stiffness, shear stiffness, and mass of a standard pneumatic wheelchair tyre. The results over multiple tests were deemed in agreement with each other, and therefore the average values of vertical and shear stiffness calculated are considered accurate (also within the range of relevant values reported in literature).

This study successfully acquired the baseline properties of a pneumatic tyre which will be used in subsequent chapters to inform the design of an FS-NPT. The feasibility of a wheelchair FS-NPT will be investigated by attempting to replicate the baseline vertical stiffness of the pneumatic tyre (relating to Objective 2 of the thesis). Before investigating feasibility, identifying the spoke geometry that will give the most favourable results is needed. A systematic literature review of FS-NPT technology will serve as a means to discover the optimum spoke design for a wheelchair FS-NPT application. This will inform the FE modelling of an FS-NPT and in turn allow predicting mechanical behaviour (Objective 1).

Chapter 5: Finite Element Modelling of Flexible Spoke Non-Pneumatic Tyres: A Systematic Review

5.1 Introduction

There are many types of FS-NPTs in literature. These tyres have unique capabilities which allow them to be used in a wide range of applications including construction, automotive, military, and aerospace. They have specific advantages for certain applications, such as their high load-bearing abilities useful for construction vehicles [39]. They also have specific disadvantages such as their inability to dissipate heat at high speeds which causes undesirable behaviour, which is detrimental in automotive applications [12].

The recent popularity of FS-NPTs is likely contributed to the fact that they do not possess the drawbacks of pneumatic tyres as they are puncture proof and virtually maintenance free. Furthermore, their spokes, which deform to absorb shocks/vibrations, can be tuned to alter the mechanical behaviour of the tyre. This tuning can allow for very specific tyre properties, but it is dependent on the spoke design. There are a multitude of spoke designs in literature which all have different tuning capabilities. Finding the optimal design for an application is an important step to ensure that the mechanical behaviour required is possible within the range of tuning. FE modelling can be an extremely useful tool to this end.

Modelling strategy is an important step in the FE process, and previous work should be studied to determine the best modelling strategies for specific designs/applications. Even though there is a number of literature reviews on non-pneumatic tyre technology [41,66,74], none of them focus on FE investigations to support the design of robust numerical modelling.

In this context, the objective of this systematic literature review is to explore the most appropriate spoke designs and modelling approaches for future FE investigations of wheelchair FS-NPTs.

5.2 Methods

The literature referenced in this review was sought through a structured approach using Scopus and ScienceDirect. Relevant articles were deemed as those which investigated non-pneumatic tyres with flexible spokes. Solid non-pneumatic tyres and mechanical wheels are also considered as 'non-pneumatic' but were not considered in the scope of the review and were therefore excluded. The specific terms used to search for relevant literature were: ("non pneumatic" OR "non-pneumatic") AND ("tyres" OR "tires"). The final search took place on 10th February 2023.

The search was limited to articles, conference papers, and reviews that were written in English. This search returned a total of 454 documents from both databases with 408 remaining after duplicate removal. These documents were screened by title and abstract first and then by reading the full paper. At the end, 80 papers were included in this review (Figure 5.1).

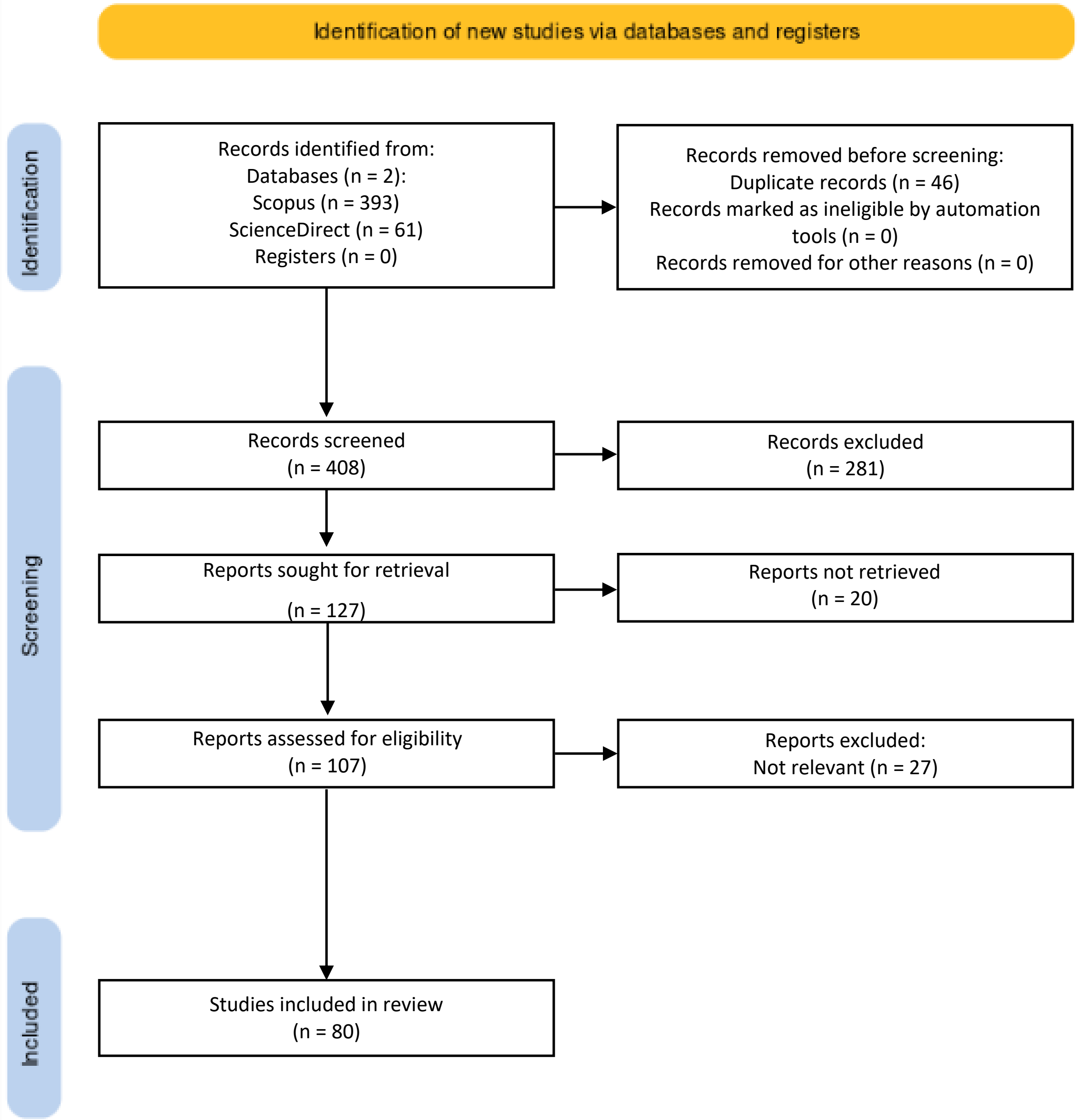


Figure 5.1 – Systematic literature review flow chart developed based on PRISMA reported guidelines [75,76].

5.3 Results

In terms of applications for FS-NPTs, 70% of studies designed an FS-NPT for automotive applications. Most studies provided different tyre dimensions for a specific automotive vehicle, such as 205/55R16 [77]. 9% of studies focused on skid steer loaders, 8% on trucks, 6% for the lunar rover, 2 focused on robot applications [78,79], 1 on all-terrain vehicles [80], and 1 on tractors [81]. There were no studies found in literature that investigated FS-NPTs in any type of wheelchair.

All the relevant papers included some form of FE analyses on flexible-spoke tyres, with the most common software's used being Abaqus and Ansys. Just over 20% of these papers included experimentation of a manufactured non-pneumatic tyre. The FE methods of these papers were divided into sections below aligned with the stages of development of an FE model.

5.3.1 Geometry Design

The design of an FS-NPT varied between applications, but almost all of them mainly consisted of 4 components. This structure of components was first used by the tyre company Michelin when they introduced the airless 'Tweel' (tyre/wheel) in 2005 [41]. These components were the hub, spokes, shear beam/band, and tread (similar structures shown in Figure 5.2). The hub is the inner part of the tyre which connects to the vehicle or device and is normally made of a stiff material and considered rigid in analyses. For this reason, some researchers modelled the tyre without the hub and instead applied a rigid connection. The spokes are connected to the hub in an array around the tyre and occupy the largest area of the tyre. The individual thin sections that make up a spoke are defined as plates; some spoke may consist of a single plate whilst others may have a multitude. The role of the spokes is to provide suspension support through elastic deformation. The shear beam/band encloses the spokes between the hub and typically consists of an inner elastomeric core and outer metallic rings (similar to a sandwich beam). Sometimes only one ring (outer ring) or reinforcement wires were used, and the role of these is to maintain the tyre shape and contact area with the ground (Figure 5.2b). The tread is the outer part of the tyre which comes into contact with the ground and provides traction. 57% of papers designed a structure that resembles the descriptions above. Due to the complex manufacturing process of FS-NPTs structured this way, several papers manufactured prototypes that were 3D printed entirely out of the same material, and so this material was used in their Finite Element (FE) models for validation. Depending on the investigation, some papers did not fully disclose the structural components. This also applies for materials, meshing strategies, loading, etc. and will not be reiterated in the following sections.

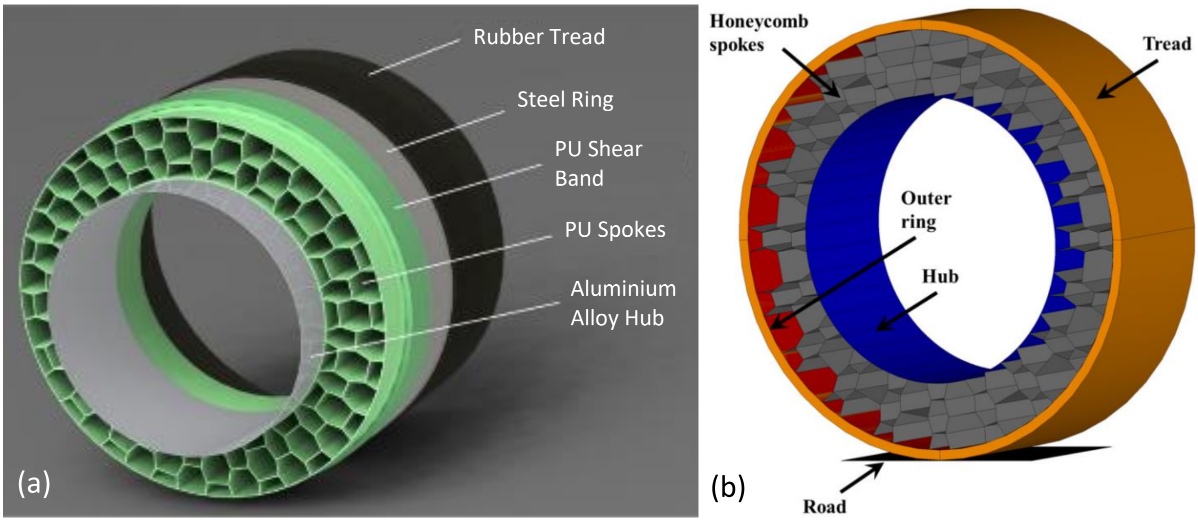


Figure 5.2 - Typical structural and material composition of an FS-NPTs in literature. (a) FS-NPT with aluminium alloy hub, polyurethane (PU) honeycomb spokes, PU shear band, steel outer ring, and rubber tread adapted from [82]. (b) FS-NPT with no shear band (same material composition) reprinted from [83]. Figure adapted by author.

The spokes were the structural part that were investigated the most in terms of geometrical design. Many studies used a pre-existing design whilst some created their own via nTopology (generative design software) or other means. Considering the range of different designs, these can be categorised into three distinctive types:

> Single plate – This design type consists of any singular plate/spoke that is repeated around the tyre (Figure 5.3). These designs have no connections between the spokes. Examples are straight radial spokes, curved spokes, angled spokes, and UPTIS design. These spokes are usually the easiest to design and manufacture but they do not have many geometric parameters for tuning (i.e., thickness, angle, curvature, number of spokes). 26% of reviewed literature used this type of spoke.

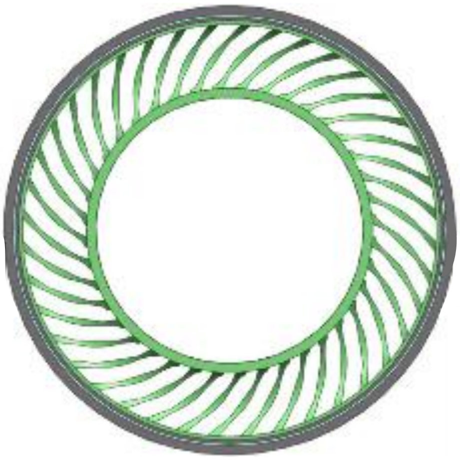


Figure 5.3 – A type of single plate design analysed in literature, reprinted from [84]. In all single plate designs, each spoke consists of a single plate.

Paired plate – This design type consists of any two plates that form a spoke and are repeated around the tyre (Figure 5.4). These two plates can be connected to each other or be separate, and there are no inter-connections between spokes. Examples are the Tweel design, triangles, crossed plates, and branched plates. These spokes have the same tuning parameters as a single plate design, with additional parameters such as the angle between the plates or the thickness of individual plates. 30% of reviewed literature used this type of spoke.

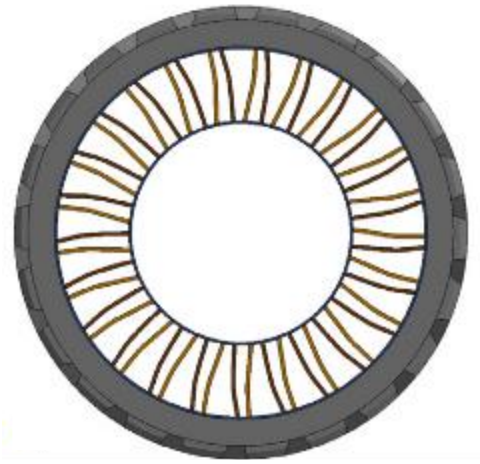


Figure 5.4 – A type of paired plate design analysed in literature (based off the Tweel design), reprinted from [37]. In all paired plate designs, a spoke consists of two plates paired together.

Multi plate – This design type consists of an intricate array of plates which interconnect to form a spoke (Figure 5.5). These designs consist of more complex geometry than the aforementioned types. Examples are honeycomb, diamond, rectangular, and other shapes which interconnect. Whilst these designs are the most difficult to design and manufacture due to their complexity, they typically have the highest capacity for tuning among available designs (increased number of adjustable internal angles, thicknesses, widths and lengths). This could allow for finer tuning to a desired mechanical behaviour and could further enable tuning the tyre to possess characteristics that cannot be achieved by the other plate configurations. 44% of reviewed literature used this type of spoke.

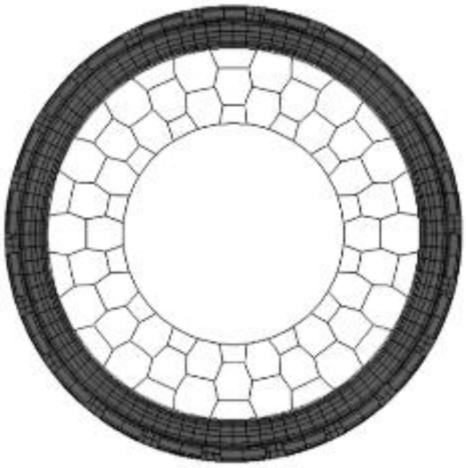


Figure 5.5 – A type of multi plate design analysed in literature, reprinted from [85]. In all multi plate designs, a spoke consists of several interconnected plates (11 plates form the honeycomb spoke in the figure, which can then be repeated to form the entire spoke assembly).

Table 5.1 shows that honeycomb, radial (hinged, curved), and the Tweel design were the three most prevalent in literature.

Table 5.1 - Spoke designs found in reviewed literature (designs which only appeared once were classed into 'other').

Spoke Type	Occurrence in literature
Honeycomb	39
Radial	27
Tweel	22
Triangle	4
Crossed	3
Rhomboid	3
Branched	2
Diamond	2
Other	6

5.3.2 Material Allocation

The role of the spokes is to provide suspension support. To achieve this, they need to be flexible. More specifically, they should deform (to a degree) under applied loads and return to the original position quickly without damage or permanent deformation. They should also be lightweight. Materials that seem to meet these requirements are elastomers such as polyurethane (PU). Almost 70% of FE models of FS-NPTs used a type of PU for the spokes. Just under 20% did not disclose the material they used. One study used steel spokes [86], and another used a different type of elastomer such as neoprene rubber [79].

Polyurethane and rubber are hyper-elastic materials and require hyper-elastic material models to accurately predict results. There are five material models that were used in the reviewed literature (Table 5.2). Out of these, Ogden material is the most common model for both the polyurethane of the spokes and the rubber of the tread. Material models can have varied accuracy depending on the loading conditions applied according to literature [87], and so this suggests that Ogden is a versatile material model for tyre loading conditions, but this does not necessarily mean that it is the optimum material model for all hyper-elastic materials and loading scenarios.

Table 5.2 – Data on non-linear material models.

Material	Model	No.	%
PU (Spokes)	Ogden	18	47
	Mooney-Rivlin	10	26
	Marlow	4	11
	Yeoh	6	16
	Neo-Hookean	0	0
Rubber (Tread)	Ogden	15	60
	Mooney-Rivlin	3	12
	Marlow	0	0
	Yeoh	0	0
	Neo-Hookean	7	28

5.3.3 Meshing

Many studies used various meshing strategies in their FE models. The most common element type, being utilised in 75% of the reviewed literature, were 3D elements. 2D elements were used in 19% of studies, and 1D elements were used in 7%. 3D elements can be divided into three types which are solid elements (68%), shell elements (26%), and surface elements (5%). Many studies used a combination of elements in their models, such as using solid elements for thick structures including the tread and shear beam and using shell elements for thin structures like the spokes, hub, and metallic rings [85,88,89]. Some studies that designed 2D FS-NPTs used 1D elements such as beam or truss elements to model the spokes and/or the metallic ring(s) [90,91,92]. Other element settings varied across literature such as the shape, of which the two shapes for solid elements were hexahedron (61%) and tetrahedron (39%). Furthermore, for appropriate elements, approximately 80% of studies used lower order (first, linear) elements with no mid-nodes, and 20% used higher order (second, quadratic).

5.3.4 Boundary conditions

In terms of setting up the simulations, 59% of studies conducted a static analysis of a vertical load, whilst almost all the remaining studies had a combination of static and dynamic loading, which usually involved adding a velocity to the tyre as a second load step to induce rolling. There were two main ways of applying a vertical load, of which the first consisted of using a master node connected rigidly to the hub and then applying a downward force/displacement. The alternative was to apply an upward force/displacement to the simulated ground. Various force magnitudes were used, but as many studies were focused on automotive applications, the weight of a vehicle divided by 4 was usually applied (typically 2 to 5 kN) [88,93]. For dynamic simulations, a similar process was followed by applying a rotation or displacement to the tyre master node or applying a displacement to the simulated ground to create a rolling effect. Typical automotive speeds of 40 to 80 km/h were frequently applied.

Contact conditions were often not disclosed, but most assumed all FS-NPT components to be bonded with each other, and a frictional contact between the tyre tread and road. The most common coefficient of friction between the tyre tread and road was set to 0.8 by 29% of studies. 16% of studies used a coefficient of 0.15. One study used a coefficient of 0, simulating a full slip condition [94].

5.3.5 Components investigated

Many studies focused on investigating the behaviour of the tyre when its geometry was altered. The majority (66%) altered the spokes in some way to determine its effect on behaviour. 23% investigated the shear band, consisting of altering the ring thicknesses or the structure. 6% altered the tread, 1 study altered the depth [95], and another altered the materials [91].

5.4 Discussion

The most common design used in literature was honeycomb. This is likely due to these structures being able to possess high strength whilst maintaining low weight. This is a useful property in tyres, as the strength is important to support the load, and its lightweight contributes to higher wheeling efficiency and lower fuel/energy consumption.

The main application of FS-NPTs is automotive, and other common themes are construction, farming, space, and ATVs. There is no evidence in literature to suggest that FS-NPTs have ever been tested or implemented on any type of wheelchair.

There are several advantages of FS-NPTs over current tyre technology. The main and obvious advantage is their inability to be punctured due to not containing air. They also do not require regular maintenance unlike pneumatic tyres. These tyres also have the ability to tune their mechanical behaviour via altering the geometry of the spokes' internal plates. Whilst a pneumatic tyre can be somewhat tuned by increasing or decreasing the internal pressurised air, the stiffnesses of the tyre (i.e. vertical, rotational/shear, and lateral) increase/decrease linearly with each other, meaning they cannot be tuned independently [96]. However, when it comes to FS-NPTs, depending on the spoke design, there are many geometrical parameters that can be modified to alter the mechanical behaviour of the tyre, and this includes altering different tyre stiffnesses independently such as the vertical and shear stiffness. These tyres also have a flat contact patch compared to the more circular pneumatic tyre shape which can contribute towards lower local stresses at the point of contact, and honeycomb designs can be tuned to reduce contact pressure [97]. This means they should wear less over time and thus last longer, and the fact that they cannot puncture also contributes to this.

Whilst FS-NPTs are a prominent technology, they do come with their disadvantages. The main disadvantage mentioned in literature is the fact that the internal spokes start to vibrate rapidly and generate excessive amounts of heat at speeds of 50mph+ [12]. This is only an issue for high-speed applications such as automotive vehicles as these are the only application that reach or surpass this speed. Many engineers are working on mitigating this issue so that these tyres can be implemented onto automotive vehicles. Another disadvantage is the fact that the tyre cannot be tuned once it has been manufactured. This is not a major disadvantage as the tyres will likely be tuned to the loads and demand of the application which is unlikely to change drastically (unless carrying loads of varied weight regularly). However, whilst the tuning process could offer a wide range of capabilities, it is also a complex process where consideration of multiple tyre stiffnesses (vertical/radial, shear, lateral) is required to optimise the behaviour of the tyre. The potential for tuning an FS-NPT based on the load on the tyre (e.g. weight of a vehicle or person depending on application) can be a big advantage in an application such as wheelchairs where the tyre can be manufactured with the behaviour that suits an individuals' needs, but this process would likely be time-consuming and expensive. Finally, many studies consider these tyres to be low maintenance, but they are not necessarily maintenance free. Checks should be carried out to ensure the spokes are not damaged, and there is the potential for debris to gather between the spokes, and so cleaning may sometimes be required (debris can clear by itself in high-speed applications but may not be the case for low-speed applications) [98]. These checks can be done quickly (by visual inspection), whereas it is not always obvious with pneumatic tyres if there is a leak or if the pressure is sub-optimal.

Regarding FE modelling, there were various types of elements, material models and loading strategies employed despite most of these studies investigating the same application (automotive). This suggests that the modelling strategy for a very different tyre application (wheelchairs) will need a separate investigation to ensure that the tyre is modelled with high accuracy. The findings presented in this review can be used as a foundation for FE model design.

5.5 Conclusion

This review demonstrates that FS-NPTs have very high potential in many applications and may potentially replace pneumatic tyres in the near future. The ability to tune the spokes of these tyres to manipulate the mechanical behaviour should allow for improvements over pneumatic and other conventional tyres. The most commonly investigated spoke design was a honeycomb structure which is likely due to its high strength-to-weight ratio and enhanced tuning capabilities over other spoke designs. These structures have numerous geometrical parameters that can be modified to tune the mechanical behaviour, and a higher number of parameters could mean a wider range of achievable mechanical behaviour, and also more precise tuning. Due to these factors, a honeycomb spoke structure appears to be the optimum structure in literature and its advantages can be applied to the application of wheelchairs. An advantage such as lower tyre weight is beneficial for active wheelchair users who require ultra-light weight wheelchairs for independence, and literature has suggested that small changes in tyre weight (0.22 kg) can have a noticeable effect on rolling resistance [6] The disadvantages of FS-NPTs are mainly for automotive applications and do not apply to low-speed applications such as wheelchairs.

Overall, FS-NPTs are likely to provide improvements to wheelchair users. More specifically, an FS-NPT with a honeycomb spoke design is likely to be most beneficial in achieving the desired behaviour according to the findings of this review. However, as these tyres have never been used in wheelchairs before, an investigation into the specific modelling strategy is required to ensure that the numerical results are reliable. The numerical findings presented in this review were mostly for automotive applications of which the dimensions and loading are significantly different, however, these strategies can act as a foundation for FE model design of the first wheelchair FS-NPT.

Chapter 6: Finite Element Modelling Techniques for Designing a Wheelchair Non-Pneumatic Tyre

6.1 Introduction

Numerous studies on FS-NPT honeycomb structures include the use of FE modelling, yet there is still a lack of knowledge regarding the requirements for accurate FE simulation of their mechanical behaviour, which most likely are application dependent. This need becomes more pronounced if one considers the range of different applications and therefore the broad range of potential sizes and mechanical requirements of honeycomb FS-NPTs. A design parameter that can strongly affect the accuracy of different modelling techniques is the relative thickness-to-height ratio (T/H, Figure 6.1a) of the honeycomb spoke. According to literature, a T/H ratio of 1/10 is considered a 'thin' plate, whilst T/H ratios larger than 1/10 are considered thick plates [99]. There is no guarantee that this threshold is the same for complex spoke geometries such as honeycomb structures, and different modelling approaches / element types are usually employed dependant on whether a structure is deemed 'thick' or 'thin'. Indeed, the mechanical behaviour of "thin" structures is commonly simulated using beam or shell elements while 2D plane or 3D solid elements are used for "thick" structures.

The selection of the most appropriate element type is strongly linked to the overall modelling approach and whether the simulated system is approached as a 2D or a 3D problem. 3D systems can be simplified and even modelled as 2D problems by taking advantage of symmetries, specifically geometry, materials distribution, and loading. In this particular case, a honeycomb FS-NPT can be simulated as a 2D computational model due to its geometric linearity in one axis (tyre depth), as well as possessing the other previously stated symmetries. This simplification can significantly improve the computational efficiency of the analysis, but it could also adversely affect accuracy. Validating the set of assumptions and simplifications against experimental results is key for ensuring the accuracy of FE modelling.

For a wheelchair FS-NPT, designing and adapting its size to suit the dimensions of a standard manual wheelchair tyre is something that has never been done before. Therefore, FE strategies need to be investigated to determine the optimum method of modelling wheelchair FS-NPTs for accurate results. Achieving the optimum modelling strategy is significant in ensuring results are as accurate as possible and computational time is minimal. The use of an inappropriate FE type can lead to misleading results and act as a barrier for robust research and development.

In this context, this chapter explores the optimum FE modelling approach and FE types for different relative dimensions of honeycomb FS-NPT spokes. To this end, the mechanical behaviour of honeycomb FS-NPT spokes will be modelled assuming that the spokes behave like thin or thick plates. They will be modelled using 3D shell elements or 2D plane elements in plane stress with thickness, which have previously been used to model FS-NPTs in other applications. FE predictions for spokes of different relative sizes will be directly compared against original experimental results to identify the best modelling approaches with the highest accuracy. Methods and results from mechanical testing will be presented first followed by the FE analysis and the comparison between numerical and experimental results.

6.2 Mechanical testing

6.2.1 Methods

Preliminary analyses and literature [73,83] showed that loading in the spokes of an FS-NPT is at its most intense in the spokes closer to the ground. To emulate this type of loading in a laboratory environment, samples of three-spoke clusters (Figure 6.1b) were produced, and their mechanical response was studied under compression. These samples were designed assuming they belonged to a hypothetical wheelchair FS-NPT with a diameter of 24 inches (inches is used as the standard measurements for wheelchair wheels/tyres) and 100 honeycomb spokes in total [100]. The design and dimensions of a reference honeycomb spoke were taken from literature to enable them to fit within a conventional 24-inch wheelchair wheel (Figure 6.1a)[83]. The spoke features several thin plates which are interconnected to form hexagonal openings centrally and between spokes. The cluster of spokes was completed with a top and a bottom support (Figure 6.1b). The inner surfaces of these supports followed the arc design of the hypothetical wheel, but their outer surfaces were flat to enable good contact between the samples and compression plates for testing under compression.

To assess the effect of T/H ratios, honeycomb designs were produced for plate thickness equal to 1mm, 1.5mm, 2mm and 2.5mm while spoke height (H) was kept constant at 18mm. All other dimensions were also kept constant (Figure 6.1a). This resulted in varied T/H ratios of the spokes, shown in Table 6.1.

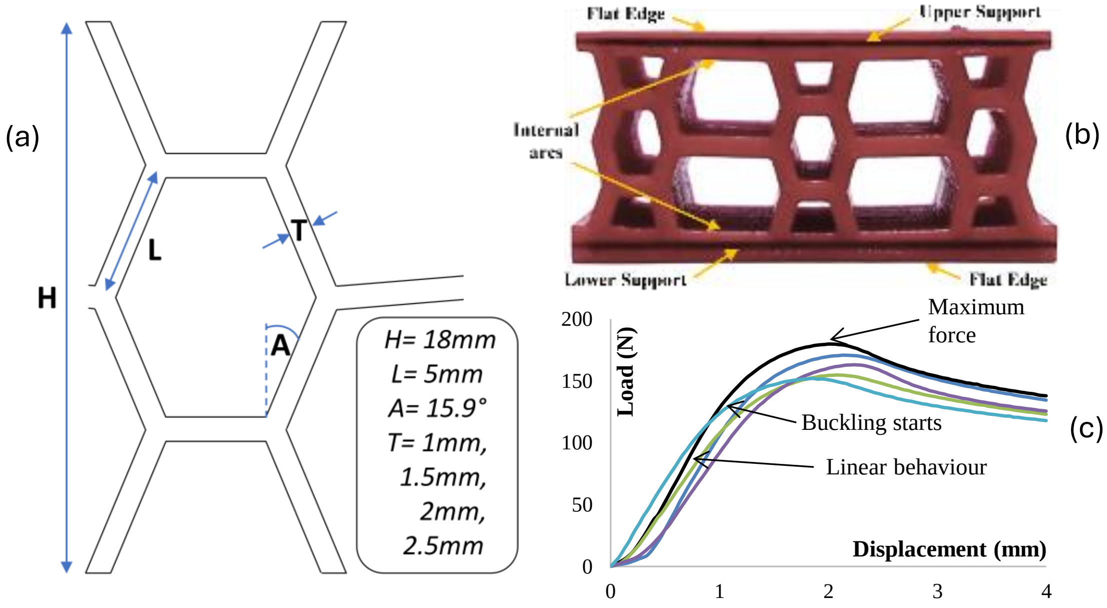


Figure 6.1 - (a) Honeycomb Spoke design. ‘H’ is the height of the entire spoke, ‘L’ is the length of the near-vertical plates, ‘A’ is the internal hexagon angle, ‘T’ is the thickness of all plates. (b) Honeycomb Spoke Cluster sample. (c) Force-displacement graph of 1mm specimen samples.

At the end, five samples of each of the four different thicknesses were tested (20 in total). Samples were produced via fused deposition modelling (Ultimaker S3) with a soft thermoplastic polyurethane (TPU95A).

To ensure the reliability of 3D printing, the plate thicknesses and depth of all samples were measured using a digital calliper. Plate thicknesses were measured for each sample at the area marked with ‘T’ in Figure 6.1 and were also measured on the plates that interconnect the spokes, and all these values were averaged to obtain an average plate thickness for a single sample.

During testing, the samples were compressed to 50% of the specimens’ height using a 10kN loading frame (Insight Electromechanical, MTS® Systems) at 2mm/min. This was to ensure post buckling behaviour was also captured. Forces and displacements were recorded using a 10kN load cell (MTS® Systems). The recorded data was used to plot the force-displacement graphs of each sample (Figure 6.1c). Five samples were printed for each thickness; the results of these were averaged to improve accuracy and ensure that any random errors (e.g. imperfections in the segments from manufacturing) did not significantly influence the final results.

Material characterisation of the 3D printing material (TPU95A) was also performed to support FE modelling. To this end, dog-bone samples were designed according to the standardized test method for tensile properties of plastics (ASTM D638).

Figure 6.2 – Dog-bone sample manufactured from TPU95A with marked lines to measure change in length.

Dog-bone samples were 3D printed using the same material and 3D printers as before (Figure 6.2). Quasi-static tensile testing (2mm/min) was carried out for three dog-bone samples using the same 10kN loading frame to measure their tensile stress-strain behaviour. Strain was measured using an optical extensometer (RTSS Videoextensometer, Limess Messtechnik & Software Gmbh). Poisson's ratio was also calculated for one sample using the same extensometer rotated 90° to measure lateral strain. At the end, the measured stress-strain behaviour (averaged over three samples) and Poisson's ratio were used to calculate the material's hyperelastic coefficients. Common hyperelastic material models that appeared in literature and were outlined in Chapter 5 were trialled, and the Mooney-Rivlin material model was most accurate in capturing the stress-strain data and was used for this reason. According to the Mooney-Rivlin model (five parameter model) [101]:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1-3)2 + C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2-3)2 + (J-1)2/d,$$

where 'W' is the strain energy potential, '$I_{1,2}$' are the deviatoric strain invariants, 'C_{10}', 'C_{01}', 'C_{20}', 'C_{11}', 'C_{02}' are material coefficients characterising the deviatoric deformation of the material, and 'J' and 'd' are the compressibility parameters.

Material coefficients were calculated using Ansys Workbench. More specifically, the experimentally measured stress-strain behaviour and Poisson's ratio were imported into ANSYS Workbench and the coefficients that achieved the best fit to the experimental data were calculated by the specialized tool within the software.

6.2.2 Mechanical testing results

The measured thicknesses are shown in Table 6.1. The standard deviation of thickness measurements ranged from 0.6% to 3.5% of their respective average. This level of variability was deemed acceptable.

All honeycomb samples buckled under loading leading to force-displacement graphs that had a clear maximum value of force (Figure 6.1c). More specifically, following bedding error (initial lack of fit between the sample surface and the compression plates) all honeycomb samples initially exhibited an almost linear increase in force with deformation. The start of buckling (≈80% of maximum force) [102] caused a gradual continuous reduction in the slope of the force-displacement graph with increased displacement (deformation). The force-displacement graphs reached a maximum value beyond which force dropped due to buckling (Figure 6.1c).

As expected, the samples became stiffer with increasing thickness. More specifically, increasing thickness from 1mm to 1.5mm, 2.0mm or 2.5mm led to an increase in maximum force of 147%, 461%, or 731% respectively. The observed substantial increase in maximum force highlights the importance of thickness for determining and optimising the mechanical behaviour of honeycomb spokes.

Tensile testing of standardised dog-bone samples confirmed that TPU95A exhibits a nonlinear stress-strain behaviour. Its Poisson's ratio was 0.45. The calculated material coefficients were as follows:

- C_{01} = 45.79MPa
- C_{02} = 62.58MPa
- C_{10} = - 36.63MPa
- C_{11} = - 58.11MPa
- C_{20} = 17.26MPa

6.3 FE modelling

6.3.1 Design of honeycomb FE models

All FE simulations were conducted using Ansys Mechanical 2021 R2. Two different modelling approaches were followed to simulate the mechanical behaviour of honeycomb spokes. More specifically the compression of the honeycomb spokes was simulated either as a 2D plane-stress-with-thickness [101] problem or as a 3D problem using shell elements. For the 2D simulation, higher order quadrilateral (quad) and higher order triangular elements were considered (Plane183) (Figure 6.3a). In these models, the honeycomb spokes and supports were meshed using the same element types and sizes. However, in the case of 3D shells, the honeycomb spokes were meshed using higher order 3D shell elements (Shell281), but the supports were meshed using 3D solid elements (Solid186). Appropriate pairs of contact elements (Conta175/Targe170) were used to ensure the correct transfer of forces and moments between the shell elements of the honeycomb spokes and the 3D solid elements of the two supports (Figure 6.3b).

The mechanical behaviour of TPU95 was simulated using the Mooney-Rivlin material coefficients that were previously experimentally calculated. For increased accuracy, the measured average spoke thicknesses and depths were assigned to the FE models (Table 6.1). For simplicity, each thickness condition is subsequently referred to using the initially assumed values (i.e. 1mm, 1.5mm, 2mm and 2.5mm).

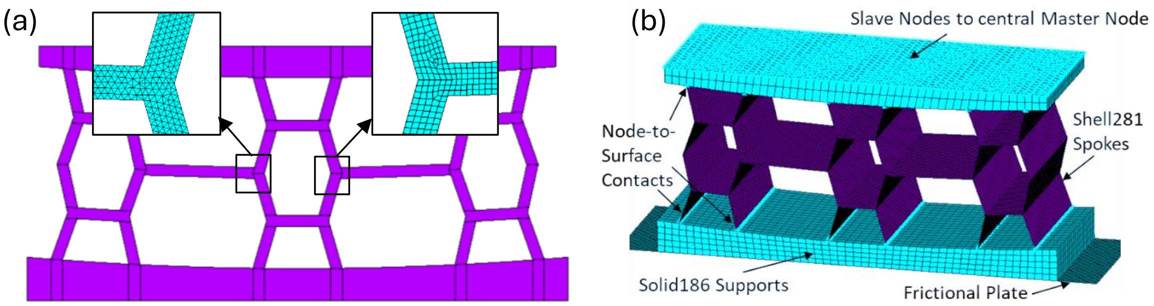


Figure 6.3 - (a) FE 2D model of a honeycomb sample showing triangular and quad mesh; (b) 3D shell model showing element types, contacts, and constraints.

To simulate compression, the models were assumed in simple contact with friction with rigid compression plates (friction coefficient=0.62 [103]). A displacement of 5mm was applied in the direction of compression to a master node connected to the top surface of the upper support via a multipoint constraint contact. The simulated bottom compression plate was fully fixed. Mesh convergence analysis was conducted to determine the most appropriate element size. The outcome measures used in the convergence analysis to determine mesh independence were the load at the point of buckling (N), and the displacement at the point of buckling (m). It was concluded that at least 13319 triangular or 27667 quadrilateral Plane183 elements were needed to minimise mesh dependency in the 2D plane models. 614 contact elements (Conta172, Targe169) were also needed. In the case of 3D Shells, 18720 Shell281, 6606 Solid186, and 12617 contact elements (Conta174, Conta175, Targe170) were needed. For an assessment of the relative computational cost of each model, the simulation time was also recorded. All simulations were done using a conventional personal computer system (Intel Core i7, 32GB RAM).

6.4 FE and Experimental Results

All simulations led to buckling and the development of a maximum force for a compressive displacement that was smaller than the maximum applied. Based on that it could be said that all models were able to qualitatively simulate the observed mechanical response of the samples.

In quantitative terms, 3D shell models were most accurate for the prediction of maximum force for the thinnest model (Table 6.1). Indeed, shell models achieved an average error of 1% while the average error of 2D plane models was 12% irrespective of the shape of the element used (quadrilateral or triangular). However, error significantly increased with thickness.

2D plane models were most accurate in the prediction of maximum force for the two intermediate thicknesses, which can be directly observed in Graph 6.1. Indeed, the absolute difference to the experiments was <3.5% for thickness 1.5mm and 2mm. For these two cases, the respective error of 3D shell models was 15% and 21%.

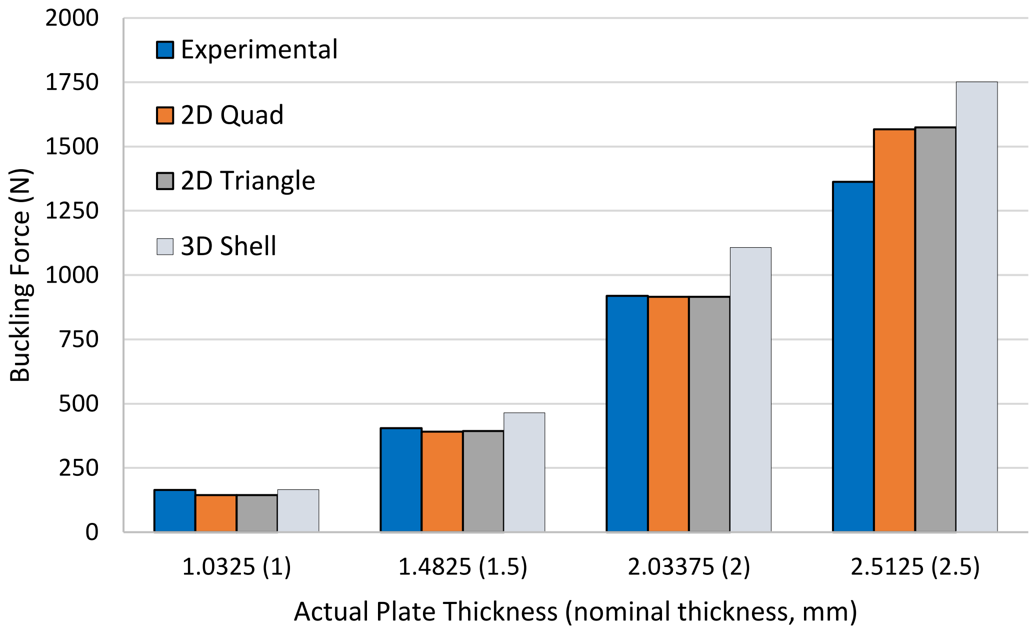
The absolute error of 2D plane models increased to 15% for the thickest samples (2.5mm). However, 2D plane models remained significantly more accurate than shell models. More specifically, the error of 2D plane elements was equal to 15% or 16% for quadrilateral or triangular elements respectively. In this case the average error of 3D shell models was 29%.

Based on these values, 2D plane elements are the preferred option for thicknesses of 1.5mm or greater, while Shell elements should be used for thicknesses of 1mm or thinner.

As can be seen from Graph 6.1, the difference between a quadrilateral mesh and a triangular mesh for the 2D analyses were negligible and therefore these shape types had almost the same error between numerical and experimental results.

Table 6.1 - The dimensions of samples and experimental and numerical result values of buckling load. In the case of thickness, the targeted values during design and the actual ones achieved with 3D printing are presented. Experimental measurements are presented by their average (±standard deviation). Numerical results are accompanied by their % difference to the respective experimental values (%Error).

Honeycomb Spoke Sample Dimensions				Buckling Load (N)			
Spoke Thickness-Designed (mm)	Spoke Thickness-Achieved (mm)	Thickness to Height ratio	Depth (mm)	Experimental	Numerical		
					2D-Quad	2D-Triangle	3D-Shell
1	1.03 ± 0.02	1 / 18	17.63	164 ±11	144 (-12%)	145 (-12%)	166 (1%)
1.5	1.48 ± 0.01	1 / 12	17.52	405 ±53	391 (-3%)	393 (-3%)	465 (15%)
2	2.03 ± 0.07	1 / 9	17.38	920 ±34	915 (-0.5%)	915 (-0.5%)	1107 (20%)
2.5	2.51 ± 0.02	1 / 7.2	17.37	1363 ±78	1567 (15%)	1575 (16%)	1752 (29%)



Graph 6.1 – Comparison of the buckling forces of the experimental results and the results of the three different FE modelling approaches (2D quad, 2D triangle, 3D shell) for the four tested honeycomb plate thicknesses.

6.5 Discussion

The purpose of this study was to determine the optimum FE method for modelling FS-NPTs designed for manual wheelchairs through comparison of experimental and numerical results. The numerical results from the higher order 3D shells have the highest accuracy for the 1mm thick plates (1% error). At the same time, 2D plane elements appeared to be most accurate for thicknesses equal or greater than 1.5mm. The accuracy of 2D plane models was reduced for the thickest scenario that was investigated (2.5mm), but they remained significantly more accurate than 3D shells (15% and 29% error respectively).

Shell elements are expected to be accurate for thickness-to-height ratios ranging between 1/10 down to 1/100 [99]. The challenge with regards to honeycomb structures is that defining the relevant height for the calculation of thickness-to-height ratios is not always straight forward. In this study, thickness-to-height ratios were defined using the height of the entire spoke as reference. Based on this assumption, the thickness-to-height ratio for 1mm thick plates was 1/18. Shell elements stopped being accurate for thickness-to-height ratio of 1/12 or larger, indicating that 2D plane elements might be more appropriate for these relative thicknesses.

An alternative way to assess this ratio would be based on the length of the individual plates of the honeycomb spoke. In this case, the thickness-to-length ratio for thicknesses equal to 1mm and 1.5mm would be ≈1/5 and ≈1/3 respectively (Figure 6.1a). These would fall out of the suggested range for using shell elements, however the results for 1mm thickness are very accurate. Due to the spoke plates being interconnected, it can be suggested that they are acting as one entity rather than single plates, which highlights the entire spoke height as a more representative measurement to inform the selection of appropriate FE types.

The numerical results and computational time of the 2D analyses were very similar for both the higher order triangular and quad elements. As far as this analysis is concerned, quads and triangular elements can be considered as equivalent.

The relative lower accuracy of the 2D models for the 1mm thickness could suggest that 2D elements are inaccurate for simulating structures with very small thicknesses. It could be further said that these elements give the most accurate results for thickness-to-height ratios of 1/12 and higher. Additional tests may be required to determine the exact threshold for where 2D elements start outperforming shell elements. For the scenarios tested here, this threshold is somewhere in the range of 1/18 and 1/12.

These findings with regards to the applicability of shell and 2D plane elements are not limited to FS-NPT applications but can be extended to the study of honeycomb structures in general. A key prerequisite for this, is that the applied loading is relevant to the compression simulated here.

6.5.1 Limitations

A limitation of this study was the exclusion of 3D solid elements within the spokes in the comparative analysis. Solid elements can be more accurate than 2D plane elements, but they are also significantly more computationally expensive. Preliminary simulations using 3D solid elements indicated that > 8 million Solid186 elements were needed to replicate the same number of elements across the thickness of honeycomb plates as in the 2D plane models resulting in a simulation time >5 hours. Considering that the ultimate goal is to use these FE models for the design optimisation of entire tyres comprising a multitude of spokes (≈100 spokes)[73], 3D solid elements were considered to be beyond the scope of this study. Another limitation of this study was that the testing of honeycomb spokes was limited to compression only. This was done because for the intended FS-NPT applications, compression appears to be the most intense type of loading [92]. However, if a vertical load is applied to a wheel causing the central hub to move downwards, an FS-NPT would be subjected to tension in the spokes at the top of the tyre and shear in the spokes at the sides [104]as well as shear deformation due to rotation. Even though it is highly unlikely that the key findings about the suitability of 2D plane and shell elements would change, the exact thresholds and optimum meshing could indeed change for different loading scenarios. The loading rate of the specimens was kept constant at 2mm/min, and so the effect of the specimens' viscoelasticity is unknown. This could be an important parameter to investigate when designing FS-NPTs for different applications as loading rates vary. However, this is the same as before, and so including the viscoelastic behaviour of TPU is likely to change the absolute values of results but it is unlikely to affect the key conclusions of this study. Last but not least, the material coefficients of TPU were calculated using data from standardised tension only. Combining data from tension and compression would improve the accuracy of the simulations.

6.6 Conclusion

The selection of an appropriate FE type for the simulation of honeycomb FS-NPT structures depends on the relative dimensions of the spoke and can significantly enhance the accuracy of the analysis. This study is the first to provide specific guidance about the type of element that should be used depending on the thickness-to-height ratios that would exist in different applications, with wheelchair tyres being an unexplored application. It was found that:

- 3D shells should be used to simulate honeycomb spokes with thickness-to-height ratios of 1/18 and below.
- 2D plane elements should be used to simulate honeycomb spokes with thickness-to-height ratios of 1/12 or larger.
- Triangular and quadrilateral elements appear to be equally accurate.
- The definition of height is very important. The above suggestions are made assuming height as the height of the entire spoke (H), not the length (L) of individual plates (Figure 6.1a).

Spoke thicknesses with a thickness-to-height ratio of 1/12 or larger for a manual wheelchair application would have a spoke thickness of 1.5mm or larger. The optimum element type to model wheelchair FS-NPTs to determine their mechanical behaviour is therefore 2D plane elements as this allows covering a significantly wider range of relevant thicknesses.

Chapter 7: Investigation of the design parameters affecting the mechanical behaviour of honeycomb wheelchair FS-NPTs

7.1 Introduction

Non-pneumatic tyres with honeycomb spoke designs have been assessed in literature. Previous studies have determined that honeycomb FS-NPT geometry can influence the mechanical behaviour when altered (Chapter 5). Literature regarding honeycomb spokes in other FS-NPT applications showed that design parameters such as angle, thickness, and length of plates, as well as the outer ring thickness and the total number of spokes can have a significant influence on the tyre behaviour [83]. To effectively tune the geometry of honeycomb spokes for a wheelchair FS-NPT, parameters that influence the relevant behaviour of the tyre should be identified (as they could vary from the literature due to different dimensions, loading, and desirable behaviour), and their specific influence should be measured. This is possible through numerical investigations, however, there is a vast number of possible combinations to consider if the effect and interplay of parameters is to be fully understood. A solution to this problem is to use Taguchi robust design methods. Taguchi methods are statistical methods which can be used to produce efficient design of experiments to study the influence of various factors on performance [105] such as the influence of honeycomb geometric parameters on tyre mechanical performance. Given a number of parameters and ranges, Taguchi fractional orthogonal arrays can be used to efficiently design a small number of experiments of which the results can provide reliable estimates for a larger dataset, which substantially reduces computational time. Before using the Taguchi method however, design parameters must be first identified and given relevant numerical ranges. Understanding the effect of specific geometry on mechanical behaviour is a crucial step to be able to effectively tune and optimise the geometry to first prove the feasibility of an FS-NPT, and ultimately to enhance its behaviour over conventional wheelchair tyre technology.

Therefore, the objective of this chapter was to explore and identify the honeycomb geometric parameters that can be used to tune the mechanical behaviour of an FS-NPT for a manual wheelchair. Understanding the behaviour and tuning the spoke geometry can lead to a wheelchair tyre that can meet the needs of wheelchair users and improve their quality of life.

7.2 Methodology

7.2.1 FE Modelling

An FS-NPT FE model was created assuming a honeycomb spoke structure that was designed to fit onto the rim of a standard wheelchair wheel with similar dimensions to a standard wheelchair tyre (width, height) (Figure 7.1a). This model utilised the optimum modelling strategy described in the previous chapter (2D plane elements with 0.2mm element size). The model featured inner and outer layers connecting to the spokes, a thin outer ring, and a tread (common structure that was outlined in the literature review). The hub was not included in the structure as the tyre would mount directly onto the wheel rim which would act as a rigid hub to the tyre. The outer diameter was set to the same diameter as the pneumatic tyre used in the laboratory experiment which was 0.607 m. The tread was set to 2.5mm thick. The outer ring and outer spoke layer had a combined thickness of 1.5mm. The height of the spokes was 18mm, and the inner spoke layer was 1mm thick (Figure 7.1b shows position of the ring and spoke layers). The depth of the tyre was 18mm which was the measured width of the wheel rim used in the laboratory experiment in Chapter 4. A rectangular area was added directly beneath the tyre model (in contact with the tread) which simulated the tread to ground/road interaction.

Material data is shown in Table 7.1. The TPU previously used for the spoke segments was used for the spokes and spoke layers. Its density value was taken from the Ultimaker TPU95A technical datasheet [106]. A steel alloy (AISI 4340) was used for the outer ring and the material properties were taken from literature [107]. Mooney-Rivlin five-parameter material model was used to simulate the TPU (derived in Chapter 6), and third-order Ogden coefficients were used to simulate the non-linear tread behaviour and were taken from literature [97].

Table 7.1 - Material properties for the components of the wheelchair FS-NPT used for FE simulations.

Component	Material	Density (kg/m^3)	Young's Modulus (GPa)	Material Coefficients	Poisson's Ratio
Honeycomb Spokes	Thermoplastic Polyurethane (TPU)	1220	-	C01=45.79MPa C02=62.58MPa C10=-36.63MPa C11=-58.11MPa C20=17.26MPa	0.45
Tread	Rubber	1043	-	μ1=13.356MPa α1=1.633 μ2=-6.631MPa α2=1.9 μ3=0.058MPa α3=2.456	0.49
Outer Ring	AISI 4340	7800	210	-	0.29

The spokes, outer-ring, and tread were simulated to be fully bonded with each other. Frictional contact was established between the ground and tread with a frictional coefficient set to 0.7 (Conta172/Targe169) [83]. A master node was created at the centre of the tyre (tyre axis of rotation) that was rigidly connected to the inner spoke layer to simulate a rigid wheel hub and enable the application of different loading scenarios (Conta172/Targe169). This also allows obtaining tyre results without the need for designing, meshing, and solving the wheel itself, which would significantly increase computational time.

The tyre was subjected to two static load steps identical to the loading conducted in the wheelchair experiment (Figure 7.1a). In load-step 1 (L1), tyre movement was prohibited in the horizontal axis (Ux=0). A downward vertical force was applied to the hub, subjecting the lower spokes of the tyre to compression. The magnitude of the applied vertical load was derived according to an average wheelchair user's weight (306N) and the calculated reaction force from one wheel in the wheelchair experiment. This load is assuming the user and wheelchair are stationary, which is a useful starting point for analysing and understanding tyre behaviour, but it is just one scenario of many every-day loading conditions (dynamic testing could have loading magnitudes much higher for tasks such as dismounting kerbs and requires future investigation). In load-step 2 (L2), a moment was applied to simulate user propulsion (25Nm) [69]. Ansys Mechanical APDL 2021 R2 was used for model design and virtual experimentation.

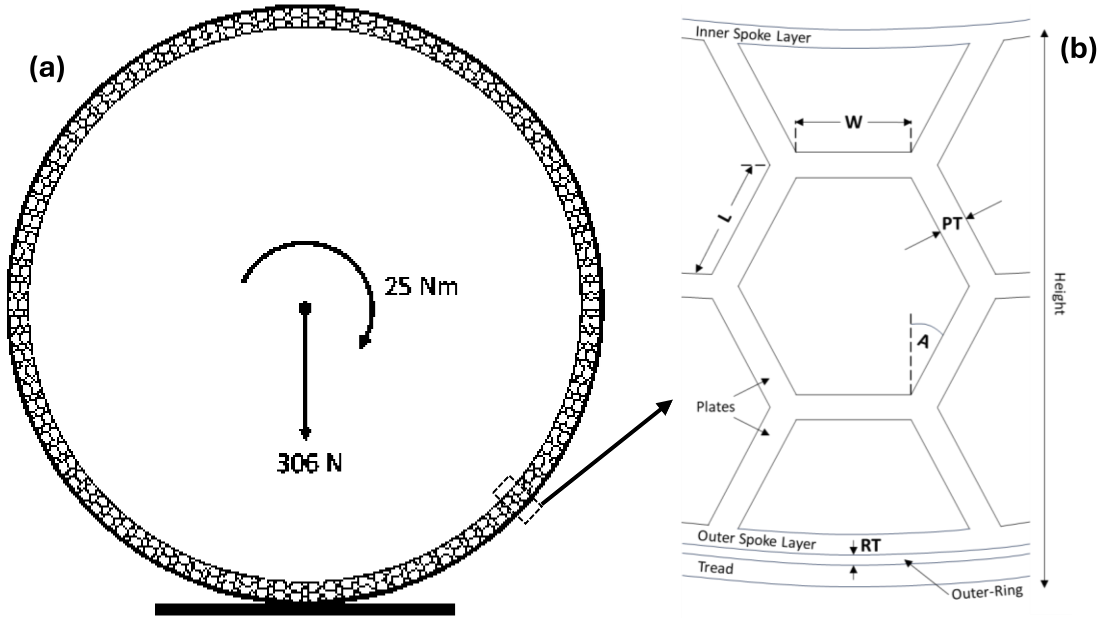


Figure 7.1 – (a) Honeycomb FS-NPT visualising loading conditions. Load step 1 is an applied downward vertical force of 306N. Load step 2 is an applied moment of 25Nm (direction irrelevant due to symmetric design). (b) Diagram of a single honeycomb spoke (shown as a segment of the whole tyre) with named sections. Parameters are highlighted that define its geometry, specifically plate thickness (PT), length (L), width (W), angle (A), and ring thickness (RT).

7.2.2 Parametric Analysis

This section defines the design parameters that were investigated for their influence on mechanical behaviour and provides these parameters with relevant numerical ranges for subsequent use in a Taguchi fractional orthogonal array.

Honeycomb design parameters were assessed for their impact on mechanical behaviour through answering the two following questions:

- Which design parameters have a significant effect on which aspects of spoke behaviour?
- Are these effects positive or negative?

Parameters that are likely to have a significant effect on tyre behaviour were sought. Geometric honeycomb parameters were previously outlined in literature [83] which were:

- Plate thickness
- Honeycomb width
- Plate length
- Honeycomb angle
- Number of spokes
- Thickness of outer ring

A design constraint of this novel wheelchair FS-NPT is that it must have similar dimensions to conventional wheelchair tyres so that the whole tyre can be mounted onto existing wheelchair wheels without altering the height of the wheelchair. Therefore, plate length must be kept constant in order to keep the height of the tyre constant, and so this parameter was excluded from the parametric analysis. The remaining five parameters, referred to from this point onwards as plate thickness, width, angle, spoke count, and ring thickness, conform to the design constraints and were included in the analysis. Figure 7.1b shows a diagram of a single honeycomb spoke that would recur 'S' number of times around the tyre, and it highlights these honeycomb design parameters.

The ranges of these parameters were derived based off three criteria:

- The range of values for which the FE model is deemed accurate.
- The range of values has to be relevant.
- The range of values should not cause any geometrical overlapping.

2D plane elements were deemed most accurate for plate thicknesses of 1.5mm and 2mm (Chapter 6). The accuracy of 2D plane elements reduced with thickness with a maximum error of 12% at 1mm thickness. The exact thickness range for which these elements can be deemed accurate can be assumed to start at the midpoint between 1mm (where error was higher) and 1.5mm. So, plate thickness can be modelled accurately within the range of 1.25mm to 2mm.

As the height of the tyre must be kept constant, altering the thickness of the outer ring would alter the height of the tyre. The thickness of the outer spoke layer and outer ring were therefore combined to always equal a thickness of 1.5mm to keep the tyre height constant (e.g., as the outer ring gets thicker, the outer spoke layer gets thinner). The thickness of metallic rings in the literature ranged from 0.5mm to 1mm [83,107], but these were for automotive applications with much higher loads. The range of thickness was therefore expanded to accommodate some smaller ring thicknesses (0.25mm to 1mm) due to the considerably lower loads that wheelchair tyres are regularly subjected to compared to automotive applications. The remaining parameters were tested to ensure plates/spokes did not overlap when values were maximised, and that they had a sufficient range to test the behaviour (the maximum plate thickness, width, angle, and number of spokes were tested as this would cause the spokes to be the widest/closest). Angle also changes the spoke structure, as an angle of 0° would result in a square shaped structure, and a width of 0 would result in a diamond shaped structure.

Table 7.2 – Identified parameter ranges for the Taguchi method.

Parameter	Minimum Value	Maximum Value	Range
Plate Thickness	1.25mm	2mm	0.75mm
Width	3mm	4.5mm	1.5mm
Angle	15°	39°	24°
Spoke Count	90	110	20
Ring Thickness	0.25mm	1mm	0.75mm

7.2.3 Design of Virtual Experiments (Taguchi)

Taguchi orthogonal arrays are based on two factors: the number of independent variables (parameters) of which there are 5, and the number of levels to be tested. The number of levels determines how accurate the results will be, but also increases the number of experiments required. There are previously defined Taguchi orthogonal arrays for which there is only one array which uses 5 parameters, and it has four levels. This array is titled L16b [108] and it includes 16 experiments shown in Table 7.3. The level numbers 1 and 4 equal the minimum and maximum values of that parameter respectively, and levels 2 and 3 would be at 33.3% and 66.7% within the range respectively. As the parameters and their ranges have already been defined for this analysis, their values for each level were calculated and are shown in Table 7.4. Substituting these levels into the orthogonal array gives the Taguchi design of experiments shown in Table 7.5. These 16 experiments were setup and conducted on the full honeycomb FS-NPT (Figure 7.1a) subjected to the 2 previously defined loading conditions. The tyre outcome measures that were recorded in these analyses were:

- Vertical Stiffness.
- Shear Stiffness.
- Maximum von-Mises stress at L1 & L2 in the spokes.
- Maximum von-Mises stress at L1 & L2 in the outer-ring.
- Maximum von-Mises stress at L1 & L2 in the tread.
- Mass of the tyre (calculated independently)

The vertical stiffness, shear stiffness, and mass were recorded for direct comparisons with the pneumatic tyre in Chapter 4. The vertical stiffness was measured at load step 1 only, and the shear stiffness was measured at load step 2 only. The stresses in the tyre need to be assessed to ensure they are below yielding point, and they also correlate to the durability of the tyre (lower stresses means increased longevity).

The mass of the tyre was calculated by multiplying the volume of individual structures by the density of their respective materials. Appendix B presents the equations for calculating mass which is based on all 5 design parameters.

Table 7.3 - Taguchi orthogonal array L16b for 5 parameters at 4 levels (P=Parameter). Numbers in the parameter columns represent the level of the respective parameter from 1 to 4.

Test No.	P1	P2	P3	P4	P5
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

Table 7.4 - Level Values of each Parameter for the Taguchi method.

	P1	P2	P3	P4	P5
Levels	Plate Thickness (mm)	Width (mm)	Angle (°)	Spoke Count	Ring Thickness (mm)
1	1.25	3	15	90	0.25
2	1.5	3.5	23	97	0.5
3	1.75	4	31	103	0.75
4	2	4.5	39	110	1

Table 7.5 - Substituted level values into L16b Taguchi Orthogonal Array. Test 1 is the reference design where all parameters were given their minimum values within their range.

Test No.	P1 (Plate Thickness)	P2 (Width)	P3 (Angle)	P4 (Spoke Count)	P5 (Ring Thickness)
1 (Ref)	1.25	3	15	90	0.25
2	1.25	3.5	23	97	0.5
3	1.25	4	31	103	0.75
4	1.25	4.5	39	110	1
5	1.5	3	23	103	1
6	1.5	3.5	15	110	0.75
7	1.5	4	39	90	0.5
8	1.5	4.5	31	97	0.25
9	1.75	3	31	110	0.5
10	1.75	3.5	39	103	0.25
11	1.75	4	15	97	1
12	1.75	4.5	23	90	0.75
13	2	3	39	97	0.75
14	2	3.5	31	90	1
15	2	4	23	110	0.25
16	2	4.5	15	103	0.5

7.2.4 Statistical analysis of outcome measures

A multiple linear regression analysis was used to assess the statistical significance of the effect of individual parameters. This analysis was repeated for each outcome measure (eight times in total excluding mass). All statistical analyses were done using IBM SPSS Statistics.

To confirm that the statistical model was accurate, several checks were made to ensure that the data was suitable for a linear regression analysis (Appendix C). Specific checks were made for:

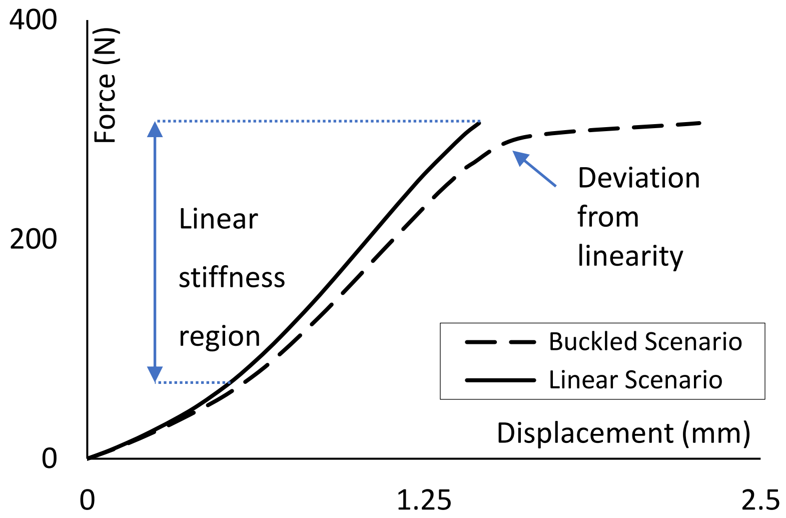
- Multicollinearity (ensuring low correlations between parameters).
- Linearity (linear relationships between parameters and results).
- Homoscedasticity (ensuring dispersion of results is consistent).

- Normality of residuals (ensuring results are consistent with normal distribution histograms / normal probability plots).
- Outliers (ensuring results are within 3 standard deviations of the mean).
- High leverage points (ensuring leverage values are low).
- Highly influential points (ensuring Cook's distance is low).

For the occurrence of outliers or any highly influential or high leverage points, multiple tests should be conducted, excluding affected cases to determine if they have a significant effect on the results.

7.2.5 Buckling Threshold Definition

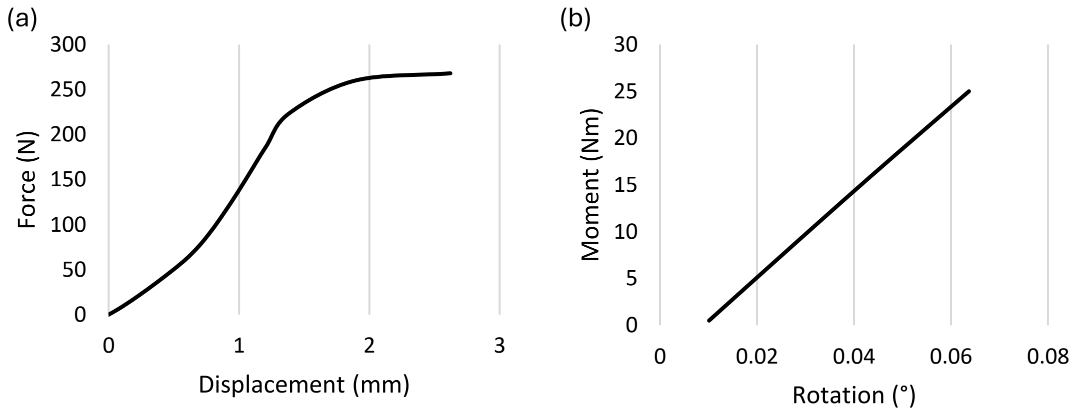
For this particular geometry, buckling of the honeycomb spokes can occur during loading. Buckling is a non-linear phenomenon which causes large deflections of structures with low thickness-to-height ratios (such as columns) when subjected to compression [109]. It is unknown at this stage if buckling will occur, and whether it will have a significant impact on the results. The buckling of the spokes can be detected by visually inspecting the deformed shape of the spokes, and/or by assessing the force-displacement graph during phase 1 of loading. Graph 7.1 shows an example of a scenario without buckling and a scenario where buckling is present. The linear stiffness region is highlighted where the line is a straight diagonal. A sudden reduction in stiffness can be indicative of buckling, and post-buckling behaviour usually adopts a secondary linear stiffness lower than the magnitude of the initial linear stiffness region (can be dependent on design).



Graph 7.1 - Example of a force-displacement graph showing a linear and buckled solution.

7.3 Results

A typical force-displacement graph is shown for load step 1 in Graph 7.2a. In this typical case, there is a linear stiffness region shortly after initial loading (around 50 N) and buckling occurs when the graph deviates from linearity (around 200 N). A typical moment-rotation graph is also presented for load step 2 in Graph 7.2b. This graph shows a completely linear relationship between the two and thus a constant shear stiffness throughout the applied moment. The graph does not start at zero as some rotation can occur from the vertical load in load step 1.



Graph 7.2 - (a) Typical Force-Displacement graph for load step 1 (displacement of the master node). (b) Typical Moment-Rotation graph for load step 2 (rotation of the master node).

The results from the 16 FE simulations were recorded and are presented in Table 7.6. Each test number corresponds to the respective case shown in Table 7.5.

Table 7.6 - FE results from the Taguchi L16b array (mass calculated from equation).

Test No.	Vertical Stiffness L1 (kN/m)	Shear Stiffness L2 (Nm/°)	Maximum exhibited von-Mises Stress (MPa)						
			Spokes L1	Spokes L2	Ring L1	Ring L2	Tread L1	Tread L2	Mass (kg)
1	95	392	37.4	37.2	317	335	0.596	0.821	0.384
2	92	608	29.1	29.0	316	325	0.574	0.495	0.449
3	131	674	23.2	22.8	287	287	0.521	0.609	0.516
4	131	749	14.7	15.2	383	382	0.596	0.711	0.587
5	259	786	12.2	12.3	317	317	0.697	0.853	0.594
6	294	781	11.4	11.4	265	265	0.621	0.750	0.546
7	116	822	22.4	22.8	236	252	0.480	0.544	0.480
8	153	789	19.8	19.7	196	219	0.529	0.561	0.428
9	226	1250	17.0	17.1	208	208	0.564	0.644	0.524
10	165	1179	17.2	17.1	182	181	0.524	0.551	0.470
11	340	806	9.5	9.6	273	273	0.795	1.028	0.616
12	240	877	14.7	14.8	281	280	0.619	0.725	0.554
13	203	1309	17.6	17.6	297	297	0.581	0.695	0.599
14	257	1042	15.8	15.9	318	318	0.704	0.887	0.636
15	297	1244	12.4	12.5	190	189	0.511	0.706	0.497
16	339	1106	10.3	10.3	202	205	0.571	0.728	0.543

7.3.1 Multiple Linear Regression

The multiple linear regression model checks were successful in determining that the data was suitable (Appendix C).

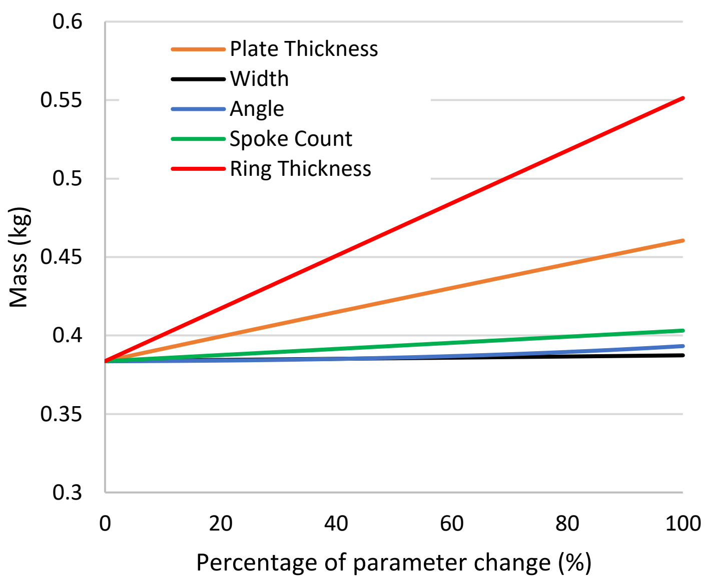
There were two experiments which were considered to have high leverage points (above 0.5) which were tests 1 and 4 (Table 7.5, Table 7.6). There were also 3 points that were considered highly influential which were test 1 for Tread Stress L2, test 4 for Ring Stress L1, and test 4 for Ring Stress L2. Combining these two factors demonstrated that there might be potential inaccuracies due to tests 1 and 4. Therefore, linear regression analysis was repeated with (all 16 scenarios included) and without these two cases (14 scenarios included).

Table 7.7 - Regression data to determine the significance and influence of parameters for the 16 tests scenario. Coefficient values (b values) of each parameter are presented which can be used to determine the direction of influence. p-values are shown in brackets which determine if a parameter is statistically significant (<0.05 threshold, significant values shown in bold).

[16 simulations] Outcome Measure	Coefficients ('p' values)					
	Constant (for equation purpose)	Plate Thickness (mm)	Width (mm)	Angle (°)	Spoke Count	Ring Thickness (mm)
Vertical Stiffness L1	-432.48	209.04 (<0.001)	15.65 (0.158)	-4.63 (<0.001)	3.10 (0.003)	92.14 (0.001)
Shear Stiffness L2	-1543.55	776.68 (<0.001)	-35.75 (0.113)	9.86 (<0.001)	11.01 (<0.001)	-80.97 (0.077)
Spoke Stress L1	107.56	-15.23 (<0.001)	-4.01 (0.02)	0.05 (0.56)	-0.44 (0.002)	-11.54 (0.003)
Spoke Stress L2	106.66	-15.13 (<0.001)	-3.92 (0.021)	0.06 (0.515)	-0.44 (0.002)	-11.31 (0.003)
Ring Stress L1	549.56	-95.92 (0.014)	-16.55 (0.328)	0.10 (0.926)	-1.54 (0.234)	138.80 (0.002)
Ring Stress L2	623.70	-106.73 (0.007)	-14.86 (0.374)	0.08 (0.939)	-2.03 (0.124)	124.08 (0.003)
Tread Stress L1	0.78	0.04 (0.32)	-0.02 (0.249)	-0.004 (0.009)	0.00 (0.258)	0.20 (<0.001)
Tread Stress L2	0.84	0.14 (0.124)	-0.03 (0.441)	-0.008 (0.011)	0.00 (0.528)	0.29 (0.006)

Table 7.7 shows parameter coefficients, and 'p' values in brackets. The 'p' value (probability value) determines the likelihood that a parameter has a statistically significant effect on the respective outcome measure. In these analyses, a 'p' value lower than 0.05 was determined to be statistically significant [110]. Plate thickness influenced all results except for stresses in the tread. Only the stresses in the spokes were influenced by the width. The angle influenced vertical and shear stiffness, and stresses in the tread. Spoke count influenced vertical and shear stiffness, and the stresses in the spokes. The outer-ring influenced all results except for shear stiffness (Table 7.7).

The coefficient values in Table 7.7 can be used to determine the positive or negative influence that a parameter has on results. A positive coefficient represents an increase in the outcome measure when the design parameter is increased, and a negative number represents a decrease in the outcome measure when a parameter is increased. Increasing plate thickness increases vertical and shear stiffness and reduces stresses in the spokes and outer-ring. Increasing width reduces stresses in the spokes. Increasing angle reduces vertical stiffness but increases shear stiffness, and also reduces tread stresses. Increasing spoke count increases vertical and shear stiffness and reduces spoke stresses. Increasing outer-ring thickness increases vertical stiffness, reduces spoke stresses, and increases stresses in the ring and tread.



Graph 7.3 - Relationship between honeycomb parameters and mass. The percentage of parameter change refers to the percentage of a parameter within its previously defined range (e.g., plate thickness at 0% would equal 1.25mm, and at 100% would equal 2mm), whilst assuming all other parameters are kept at their minimum.

Graph 7.3 shows the effect that design parameters have on the mass of the tyre throughout their range, all starting at the reference design with a weight of 0.384 kg. The mass was calculated using the equations in Appendix B. Outer ring thickness, plate thickness, and spoke count increase with increasing mass. Out of these three design parameters, outer ring thickness and plate thickness appear to have the strongest effect on mass leading to tyre designs substantially heavier than the reference pneumatic tyre of Chapter 3 (0.408 kg). The effect of width and angle could be considered negligible. Each parameter had a linear relationship except for angle.

7.3.2 Taguchi Repeat Test (14 cases)

The Taguchi test was repeated excluding simulations which had high leverage and highly influential points to determine if they had a significant effect on the results. Table 7.8 shows the results for this repeat test in the same format as the previous test (showing coefficients and 'p' values).

Table 7.8 - Regression data to determine significance and influence of parameters for the 14 tests scenario.

[14 Simulations]		Coefficients ('p' values)				
Outcome Measure	Constant	Plate Thickness (mm)	Width (mm)	Angle (°)	Spoke Count	Ring Thickness (mm)
Vertical Stiffness L1	-590.56	193.09 (<0.001)	28.72 (-0.154)	-3.82 (0.010)	4.10 (0.019)	118.28 (0.012)
Shear Stiffness L2	-1173.85	740.50 (<0.001)	-56.91 (0.153)	8.54 (0.005)	9.39 (0.009)	-123.30 (0.125)
Spoke Stress L1	93.80	-12.88 (0.005)	-3.35 (0.241)	0.10 (0.579)	-0.39 (0.088)	-10.22 (0.090)
Spoke Stress L2	95.80	-12.65 (0.005)	-3.48 (0.214)	0.09 (0.601)	-0.41 (0.072)	-10.43 (0.078)
Ring Stress L1	812.27	-52.48 (0.076)	-40.43 (0.081)	-1.40 (0.302)	-3.37 (0.061)	91.03 (0.055)
Ring Stress L2	901.53	-62.67 (0.033)	-39.88 (0.072)	-1.49 (0.252)	-3.95 (0.028)	74.03 (0.091)
Tread Stress L1	1.09	0.06 (0.257)	-0.05 (0.240)	-0.01 (0.049)	0.00 (0.246)	0.16 (0.073)
Tread Stress L2	-0.35	0.24 (0.009)	0.04 (0.519)	0.00 (0.325)	0.00 (0.451)	0.43 (0.005)

In this repeat test (which consisted of 2 less simulations in attempt to increase accuracy by eliminating high leverage and highly influential points), there are a lower number of statistically significant results. All results that remained significant had the same influence as previously stated. The differences were: plate thickness did not influence ring stress L1 but did increase stresses in the tread for L2. Width was not statistically significant at affecting any of the results. Angle did not influence tread stress L2 in this test. Spoke count did not influence spoke stresses but did reduce stresses in the ring for L2. The outer ring did not influence spoke, ring, and tread L1 stresses in this repeat test.

7.3.3 Buckling

Following the inspection of the deformed shapes of the spokes and respective force – displacement graphs for all simulated scenarios, it was concluded that three simulations led to buckling. These were scenarios 1, 2, and 7. Based on these, a potential threshold for buckling was identified. It was concluded that any spoke design with a vertical stiffness value equal or lower than 122 kN/m is likely to have undergone buckling.

7.4 Discussion

Table 7.6 shows the first set of results for an FS-NPT designed for a wheelchair. The vertical stiffness ranged from 92 to 340 kN/m, the shear stiffness from 392 to 1309 Nm/°, and the mass from 0.384 kg to 0.636 kg. Compared to the pneumatic tyre experiment in Chapter 4, the pneumatic tyre had a vertical stiffness, shear stiffness, and mass of 139 kN/m, 32 Nm/°, and 0.408 kg respectively. The pneumatic tyre vertical stiffness falls within the range of the wheelchair FS-NPT, but it is towards the lower end, and near to the buckling threshold of 122 kN/m. All FS-NPT parameter combinations appear to be significantly stiffer in shear. As a higher shear stiffness results in better wheeling efficiency, this means that honeycomb FS-NPTs are likely to have better wheeling than standard wheelchair pneumatic tyres within the range of parameters. The FS-NPT is also capable of being lighter than the pneumatic tyre, although most scenarios were heavier which can limit the range of tuning if a lower mass is to be achieved.

7.4.1 Effect of design parameters

The multiple linear regression analysis was performed to determine the significance and direction influence of the geometrical parameters on results. Table 7.6 shows the 'p' values and coefficients necessary to predict the behaviour of the tyre which were defined based on the Taguchi L16b fractional orthogonal array. This array has been successfully used in previous literature to analyse experimental data efficiently [111]. Out of the 40 results (5 parameters x 8 output results), 23 were deemed significant in having an effect on tyre results. The parameter which seemed to be the least influential was the spoke width, as it only had an effect on stresses in the spokes and led to a small change in mass. The most influential parameter was the outer-ring, having an effect on all results except for shear stiffness. An important aspect of the tuning of an FS-NPT is the ability to decouple vertical and shear stiffness to allow optimising both these properties, which is impossible to do in pneumatic tyres through pressure manipulation alone (as tyre directional stiffnesses tend to increase linearly with increasing pressure) [96]. The angle of the internal hexagon is the only parameter to influence vertical and shear stiffness in opposite directions, meaning it could be altered along with the other geometric parameters such as plate thickness to tune these two stiffnesses separately, giving the potential for optimising both comfort and propulsion efficiency simultaneously. As the mass of the structure negligibly changes with changing angle (Graph 7.3), tyre stiffnesses can be altered without adding any additional weight. The fact that angle can also easily take a continuous range of values highlights it as an ideal design parameter for finetuning of the tyre's mechanical characteristics. Desirable tyre properties such as high shear stiffness (for efficient propulsion), and low stresses (for prolonged tyre life) require increasing the thickness of the spokes, but this will increase the mass of the structure which is deemed undesirable. A separate investigation is needed to explore how to achieve the desired levels of stiffness while keeping mass as low as possible.

For the Taguchi repeat test, the results in Table 7.8 show that 14 of the of 40 results are considered significant compared to the 23 from the initial test. This test has not specifically revealed any large differences. The most important difference was the fact that width stopped having a significant effect for any of the outcome measures. Further exploration is needed, including a bigger sample of different geometric designs to conclude whether/how spoke width affects the mechanical behaviour of the wheelchair FS-NPT.

7.4.2 Limitations

In these analyses, the FS-NPT was tested under static loading only. Static loading is an important foundation for FE analyses and can in this case provide good insight into the mechanical behaviour of the tyre under compression and shear loading. However, further research will be needed that includes dynamic simulations to provide more insight into the behaviour of the tyre during propulsion and navigating obstacles and different terrain. Such simulations were deemed to go beyond the scope of this thesis.

The behaviour of buckled tests will have likely impacted the results and the accuracy of the coefficients due to its non-linear nature. Future analyses should exclude buckled cases. Moreover, a larger sample size will be needed to provide an accurate estimation of the regression coefficients.

7.5 Conclusion

The objective of this chapter was to explore and identify the honeycomb geometric parameters that can be used to tune the mechanical behaviour of an FS-NPT for a wheelchair. The main findings from this chapter were as follows:

- Plate thickness, width, angle, spoke count, and ring thickness are parameters that influence the mechanical behaviour of honeycomb spoke geometry.
- Plate thickness can be increased to increase vertical and shear stiffness. Increased thickness also decreases stresses for better durability, but it also increased tyre mass.
- Width can potentially reduce stresses in the spokes but had no effect according to the repeat test. The change in mass is negligible.
- Angle can be increased to decrease vertical stiffness and increase shear stiffness without influencing the mass.
- Spoke count can be increased to increase vertical and shear stiffness and reduce spoke stresses.
- Outer-ring thickness can be increased to increase vertical stiffness and potentially reduce stresses in the spokes. Increasing thickness consequently increases stresses in the outer-ring and tread as well as increasing tyre mass.

These findings highlight the effect that each honeycomb design parameter has on the mechanical behaviour of the tyre. Furthermore, this study strongly suggests that all design parameters are likely to be influential in altering the behaviour of the tyre in some way and can be used to modify the performance of the tyre. However, the regression model here is based on a relatively small number of simulations. To fully understand the significance and specific influence of tyre parameters on the mechanical behaviour to allow for accurate tuning, more simulations should be conducted to build upon this model. Understanding the effect of geometry on performance is an important step and provides the foundation necessary for tuning and optimising the tyre behaviour. This is needed to provide tyre characteristics that users deem desirable, with the end goal of improving their quality of life.

Chapter 8: Tuning of a Flexible Spoke Non-Pneumatic Tyre for Manual Wheelchairs

8.1 Introduction

The previous chapter identified the design parameters that are likely to have a significant effect on the mechanical characteristics of a wheelchair FS-NPT. The statistical model that was used for the previous analysis utilised the Taguchi design of experiments method. This method is a useful starting point, but if the behaviour of the tyre is to be predicted accurately, more simulations are required to create a robust regression model that accurately quantifies the specific effect of each design parameter on different key outcome measures.

The first objective of this chapter was to test whether FS-NPTs can replicate the mechanical characteristics of existing wheelchair tyres. To achieve this, the robust regression model will be used to determine the design dimensions that provide the same mechanical behaviour of the wheelchair pneumatic tyre that was tested in Chapter 4, specifically the vertical stiffness. Being able to replicate the vertical stiffness of the pneumatic tyre demonstrates that a wheelchair FS-NPT can provide similar suspension properties to users which contribute to their comfort level. As the vertical stiffness is one of the most important properties of a pneumatic tyre which defines its behaviour, having an FS-NPT which can also attain this stiffness is the first step in proving its feasibility. The second objective of this chapter was to explore the potential improvements to user experience that wheelchair FS-NPTs could offer. One such improvement is improved propulsion efficiency which can increase user independence and inclusivity whilst mitigating fatigue and injury. This can be achieved by having a tyre with higher shear stiffness. The mass of the tyre also contributes to user independence, as lightweight tyres are easier to transport and generally easier to propel. A tyre with high durability is a potential benefit that can increase the life of the tyre, reducing wheelchair maintenance, and improving financial and environmental aspects.

The vertical stiffness was the only characteristic which was to be tuned to a precise value (to prove feasibility), whilst the other characteristics were objectives to be maximised or minimised. In Chapter 7, the Taguchi test indicated that shear stiffness was significantly higher than the pneumatic tyre over the entire range of FS-NPT FE designs, strongly suggesting that the FS-NPT will have a higher shear stiffness regardless of the parameter values (within their range). Therefore, this characteristic does not need to be prioritised during tuning. According to Chapter 7 findings, the mass of the pneumatic tyre fell into the mass range of the FS-NPT, but it was very close to the lowest possible mass within the range of parameters. Achieving an FS-NPT with the same or lower mass is critical in highlighting that an FS-NPT can be a more suitable tyre technology and is also an objective benefit that users can understand, relate to, and directly compare themselves. Therefore, the tuning priority was to achieve the vertical stiffness of the pneumatic tyre with the same or lower mass.

8.2 Methodology

A multiple linear regression model was produced using IBM SPSS Statistics. To obtain a more accurate and robust regression model, more simulations were needed from the initial analysis in the previous chapter. The initial 16 simulations had three buckled scenarios (runs 1, 2, and 7), so these were excluded prior to the analysis. To assess the accuracy of this regression model, coefficient values can be used to predict the behaviour of the tyre utilising the multiple linear regression equation and can be directly compared with the FE results:

$$y = \beta_0 + \beta_1 P_1 + \beta_2 P_2 \dots\dots\dots \beta_n P_n$$

$$y = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + \beta_3 P_3 + \beta_4 P_4 + \beta_5 P_5$$

In this equation, ‘β’ is the coefficient value, ‘P’ is the parameter value, and ‘y’ is the outcome measure. The numbered subscripts refer to the parameter number (i.e. plate thickness is parameter 1):

Regression analysis was repeated after increasing the sample size in increments of 10. The values of the design parameters for each one of these simulations were defined using a random number generator which assigned random values for each parameter within the previously defined ranges (Table 8.1). Simulations where the spokes buckled were excluded and replaced with new random design parameters until a complete set of 10 new scenarios was completed.

To estimate the sample size that can produce a robust regression model, an additional set of 10 random scenarios (that were not used to define the regression model) was also tested and used for validation (Table 8.1). More specifically, the regression analysis was repeated for each incremental increase of sample size and the new regression coefficients were used to predict the outcome measures of the validation set. Plotting the prediction error over increasing sample size should enable detecting the minimum number of simulations that are needed to produce a reliable regression model.

Table 8.1 - 10 combinations of parameters created using a random number generator for the assessment of prediction error.

Test No.	Plate Thickness	Width	Angle	Spoke Count	Ring Thickness
1	1.65	4.13	16.63	96	0.25
2	1.88	3.86	31.59	95	0.95
3	1.30	3.91	23.46	106	0.32
4	1.69	3.04	31.95	110	0.32
5	1.36	3.64	29.93	108	0.34
6	1.29	3.95	18.45	99	0.90
7	1.56	4.17	27.34	96	0.48
8	1.48	3.88	35.64	100	0.96
9	1.45	4.47	35.31	99	0.90
10	1.74	4.22	28.85	92	0.83

8.2.1 Tuning to Targeted Characteristics

The targeted characteristics of this FS-NPT were as follows:

- Vertical Stiffness should be equal to the pneumatic tyre.
- Mass should be the same or lower.
- Shear stiffness should be the same or higher.
- Maximum stresses should be lower than material strength.

To acquire an FS-NPT that possesses the pneumatic tyre vertical stiffness of 139 kN/m and the lowest mass, all parameters that significantly affected the mass were minimised. The parameters that influenced the vertical stiffness with minimal influence on mass were used to tune the vertical stiffness. The regression model was used to predict parameter values that resulted in the exact vertical stiffness with the lowest mass. Additional simulations were performed to account for error in the regression model.

8.3 Results

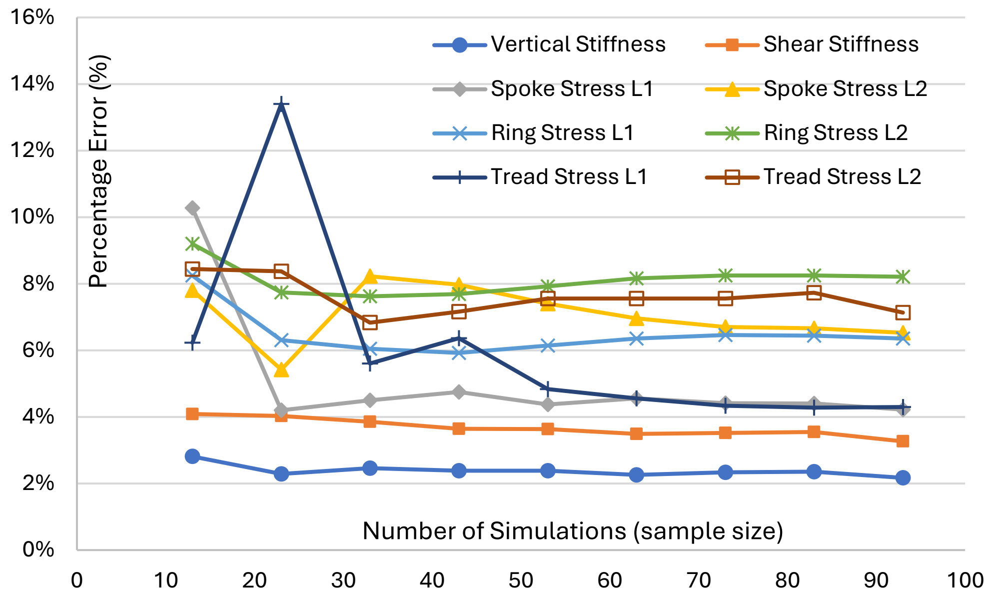
8.3.1 Robust Regression Model

The final regression model utilised data from 93 simulations. In Table 8.2, a range of stiffness, stress, and mass values are shown. Vertical and shear stiffness had the lowest errors at approximately 2% and 3% respectively. Prediction of stresses in the outer-ring during load step 2 had the highest error at approximately 8%.

Table 8.2 – Finite element results for the ten randomly generated combinations of parameters for calculating regression model error. The percentage error (absolute) for the regression model based on 93 simulations is shown in the last row. Mass values were calculated using the mass equation.

Test No.	Vertical Stiff-ness (kN/m)	Shear Stiff-ness (Nm/°)	Maximum von-Mises Stress (MPa)						Mass (kg) (from equation)
			Spoke L1	Spoke L2	Ring L1	Ring L2	Tread L1	Tread L2	
1	253	804	14.6	14.7	189	206	0.534	0.693	0.437
2	240	1042	16.0	15.9	328	328	0.678	0.804	0.622
3	170	650	16.0	16.7	215	240	0.499	0.727	0.425
4	207	1211	16.7	16.6	181	181	0.437	0.649	0.478
5	161	819	15.9	16.5	230	249	0.467	0.650	0.441
6	214	537	14.2	15.4	324	324	0.619	0.754	0.545
7	186	863	16.4	16.0	217	220	0.535	0.593	0.481
8	167	863	16.7	16.5	362	361	0.631	0.763	0.590
9	155	818	17.7	17.4	349	349	0.593	0.711	0.573
10	215	937	14.4	14.5	314	313	0.608	0.733	0.575
% Error	2.17%	3.27%	4.22%	6.53%	6.35%	8.21%	4.30%	7.13%	-

In Graph 8.1, the percentage errors gradually reduced for all results with increasing sample size. The vertical stiffness changed the least, and only reduced by 0.64% error when adding 80 sets of simulations to the regression model. Stresses were more unstable initially and had a larger error than stiffnesses throughout the different regression model stages. Stabilisation of error (low change in error, progressing towards horizontal line on the graph between error points) could be said to occur between 53 and 93 simulations.



Graph 8.1 – Statistical model percentage error on predicting the outcome measures (L1 and L2 represent load-steps 1 & 2 respectively). Actual FE results were compared with the regression model predictions at each stage for all outcome measures and the percentage errors were calculated.

Table 8.3 shows the coefficient and 'p' values generated by the regression model with data of 93 simulations. These are presented as they are used in the linear regression equation to predict result values and can be directly compared with the findings from the Taguchi method in Table 7.7.

Table 8.3 - Coefficient and 'p' values for 93 simulations.

[93 sims.] Outcome Measure	Coefficients ('p' values)					
	Constant (equation purposes)	Plate Thick-ness (mm)	Width (mm)	Angle (°)	Spoke Count	Ring Thick-ness (mm)
Vertical Stiffness	-114.318	159.395 (<0.001)	-4.305 (0.004)	-5.690 (<0.001)	2.054 (<0.001)	58.380 (<0.001)
Shear Stiffness	-1308.374	774.410 (<0.001)	-32.482 (<0.001)	10.347 (<0.001)	8.920 (<0.001)	-118.884 (<0.001)
Spoke Stress L1	31.808	-3.977 (<0.001)	0.131 (0.631)	0.295 (<0.001)	-0.159 (<0.001)	-3.729 (<0.001)
Spoke Stress L2	33.598	-5.410 (<0.001)	0.580- (0.122)	0.302 (<0.001)	-0.175 (<0.001)	-3.009 (<0.001)
Ring Stress L1	134.440	-29.537 (<0.001)	3.223 (0.367)	1.089 (<0.001)	-0.041 (0.881)	210.962 (<0.001)
Ring Stress L2	168.626	-36.466 (<0.001)	2.472 (0.510)	1.054 (<0.001)	-0.132 (0.646)	198.584 (<0.001)
Tread Stress L1	0.398	0.082 (0.007)	-0.030 (0.025)	-0.004 (<0.001)	0.001 (0.383)	0.280 (<0.001)
Tread Stress L2	0.365	0.146 (<0.001)	-0.006 (0.568)	-0.006 (<0.001)	0.001 (0.336)	0.301 (<0.001)

Table 8.4 shows the specific influence of parameters that were statistically significant. The percentage values were calculated by increasing a parameter by 10% of the range from the reference design (Table 7.5 - Test No. 1) and inputting the generated coefficients into the regression model equation to predict the change in each outcome measure. For example, increasing plate thickness by 10% of its range (0.075mm) from the reference design (1.25mm) would equal 1.325mm. According to the table, this change would increase the vertical stiffness by 12.52%. The data in Table 8.4 is significant in determining the parameters which can be used to tune the mechanical behaviour of the tyre. Plate thickness can tune all outcome measures, but more specifically, can be increased to increase the vertical and shear stiffness of the tyre by a similar magnitude of 13% and 15% (to the nearest percentage). The width can be increased to reduce both stiffnesses and reduce stresses in the tread (L1), but the magnitudes of these reductions are relatively small (<2%), and mass is

also minimally affected. Angle can also tune any outcome measure, but mainly can be increased to reduce vertical stiffness by a large magnitude (-14%) and increase shear stiffness by a considerable magnitude (6%), with a negligible change in mass. Spoke count can be increased to increase both stiffnesses by a similar magnitude (4 - 5%) with a small increase in mass (<1%). The outer ring thickness can be increased to increase vertical stiffness and reduced shear stiffness and has the largest increase in stress for the ring and tread components (up to 5%). It also resulted in a higher mass increase compared to any other parameter (4%).

Table 8.4 – The significance, influence, and direction of honeycomb geometric parameters on tyre outcome measures based on 93 FE simulations. The percentage values shown were calculated based on the parameters having their minimum values (reference design). Each parameter was increased by 10% of its previously defined range. The regression model was used to calculate the change in each outcome measure from this parameter increase. Cells marked with a hyphen (-) indicate no statistical significance between the parameter in the cell column and the outcome measure in the cell row. Mass was calculated from the mass equation.

Outcome Measure	Parameter				
	Plate Thickness (mm)	Width (mm)	Angle (°)	Spoke Count	Ring Thickness (mm)
Vertical Stiffness	12.52%	-0.68%	-14.31%	4.30%	4.59%
Shear Stiffness	14.80%	-1.24%	6.33%	4.55%	-2.27%
Spoke Stress L1	-0.80%	-	1.90%	-0.85%	-0.75%
Spoke Stress L2	-1.09%	-	1.95%	-0.94%	-0.61%
Ring Stress L1	-0.70%	-	0.83%	-	5.00%
Ring Stress L2	-0.82%	-	0.76%	-	4.45%
Tread Stress L1	1.04%	-0.76%	-1.51%	-	3.53%
Tread Stress L2	1.33%	-	-1.69%	-	2.75%
Mass (from equation)	2.05%	0.097%	0.028%	0.51%	4.37%

8.3.2 Tuning Results

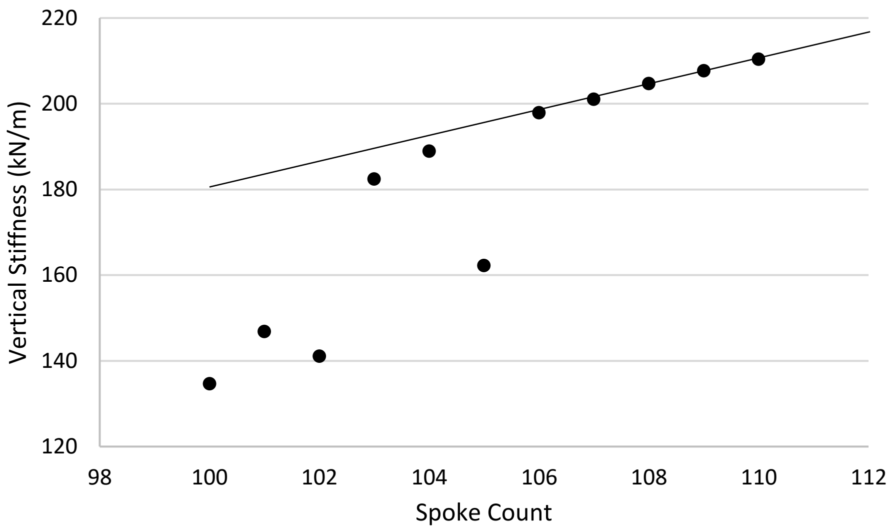
The combination of parameters with the lowest mass can be obtained through observation of the influence of parameters on mass in the last row in Table 8.4.

All parameters were initially minimised as they all increased mass when increased. This combination of parameters is the same as the reference design (test no. 1 in

Table 7.5 in Chapter 7), and this simulation had buckled and had a lower vertical stiffness than the target value (95 kN/m), but it also had a lower mass (0.384 kg). Using that scenario as reference, changes are needed to the design parameters to increase stiffness with the smallest possible increase in mass. The parameter that can influence vertical stiffness the most with the lowest change in mass is the internal angle, however this influence was negative, and a larger angle results in a softer structure. According to Table 8.4, plate thickness had the largest positive influence on vertical stiffness, but it also significantly increased the mass. Increasing spoke count also led to increased stiffness, but in this case the effect on mass and stiffness appeared to be lower. To determine which parameter can increase vertical stiffness with the lowest increase in mass, the achieved gain in vertical stiffness for the same amount of increase in mass was calculated for both parameters. This was calculated by dividing the percent increase in vertical stiffness by the respective increase in mass caused by 10% change in plate thickness or spoke count (Table 7.4). Based on that it was calculated that for every 1% increase in mass due to increased plate thickness or spoke count, vertical stiffness increases by 6.11% or by 8.43% respectively. Based on this, it can be concluded that increasing spoke count is a more efficient way for increasing vertical stiffness while keeping mass low.

Plate thickness was therefore assigned its minimum value (1.25mm) and spoke count was used to increase the vertical stiffness to the target value.

As the combinations of parameters set to minimum can cause the spokes to buckle, the linear regression model was not used as it was unable to accurately predict the effect of buckling behaviour. Simulations were required to determine the value of spoke count which prevents buckling. Graph 8.2 shows several simulations that were carried out to present the linear and non-linear behaviour of the geometry based on spoke count. All other parameters were kept constant at their minimum for these simulations. It can be seen that the lowest spoke count value within the linear region was 106 spokes.



Graph 8.2 – The effect of spoke count on vertical stiffness. Trendline shows spoke count values below 106 deviate from linearity (spokes have likely buckled).

The vertical stiffness that corresponded to this spoke value was 198 kN/m which exceeded the target vertical stiffness. Angle was increased to reduce the vertical stiffness to its target value. The regression model equation was rearranged to set angle as the subject and the vertical stiffness target value as the input to determine the required angle, where 'y' is the vertical stiffness and 'P3' is the angle (parameter 3). The coefficients from Table 8.3 were used.

$$y = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + \beta_3 P_3 + \beta_4 P_4 + \beta_5 P_5$$

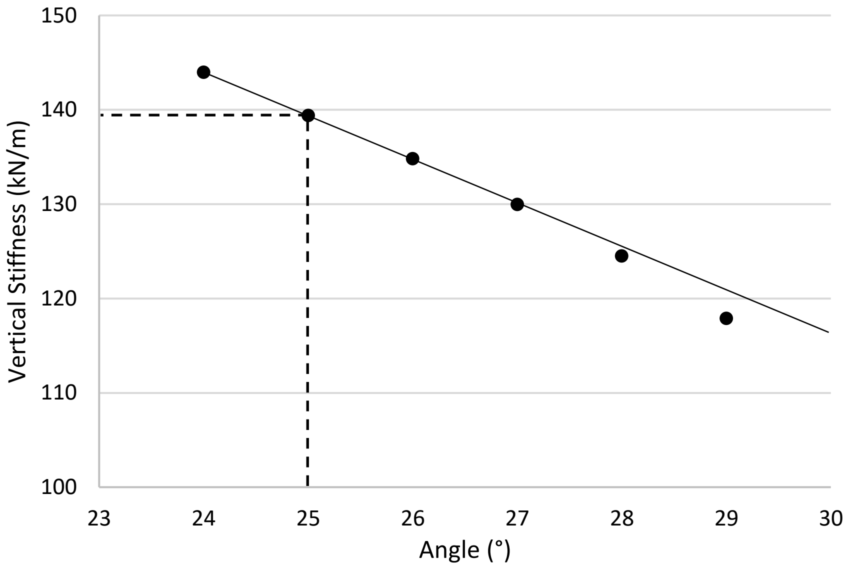
$$P_3 = \frac{y - \beta_0 - \beta_1 P_1 - \beta_2 P_2 - \beta_4 P_4 - \beta_5 P_5}{\beta_3}$$

$$P_3 = \frac{139 - (-114.318) - (159.395 \times 1.25) - (-4.305 \times 3) - (2.054 \times 106) - (58.38 \times 0.25)}{-5.690}$$

$$P_3 = 29.06°$$

This outputted an angle of 29.06°. This simulation was attempted (with a spoke count of 106 and minimum values for the other three parameters) and the vertical stiffness value was 118 kN/m. This was lower than the target value that the regression model had predicted by 15%, and so the angle was reduced in increments of 1° until the target vertical stiffness was achieved within 1 kN/m. Graph 8.3 shows that the angle was approximately 25° with a vertical stiffness of 139 kN/m. It also shows that a tyre with this angle is within the linear stiffness region (deviation from linearity begins at an angle of 28°+) demonstrating that the spokes have not buckled. The combination of parameters that give the target vertical stiffness with the lowest mass are as follows:

- Plate thickness = 1.25mm
- Width = 3mm
- Angle = 25°
- Spoke count = 106
- Ring thickness = 0.25mm



Graph 8.3 - The effect of angle on vertical stiffness (linear line shows where a higher angle departs from linearity due to buckling).

Table 8.5 shows the results of the tyre with the target vertical stiffness and lowest possible mass (target FS-NPT). The mass of this tyre design was 0.401 kg which is marginally lighter in weight than the tested pneumatic tyre. As expected from Chapter 7, the shear stiffness of this target FS-NPT is substantially higher than the pneumatic tyre shear stiffness.

Table 8.5 - Results of the FS-NPT with the targeted vertical stiffness and lowest mass in comparison with the mechanical properties of the standard wheelchair pneumatic tyre.

Tyre Type	Vertical Stiffness (kN/m)	Shear Stiffness (Nm/°)	Maximum von-Mises Stress (MPa)						Mass (kg)
			Spokes L1	Spokes L2	Ring L1	Ring L2	Tread L1	Tread L2	
FS-NPT	139	665	19.5	19.4	278	296	0.563	0.780	0.401
Pneumatic	139	32	-	-	-	-	-	-	0.408

The zoomed section in Figure 8.1 is the area of the tyre where the components are most affected by the loading. Small bending of the honeycomb plates can be observed. Subsequent results show the exhibited stresses in this highlighted area.

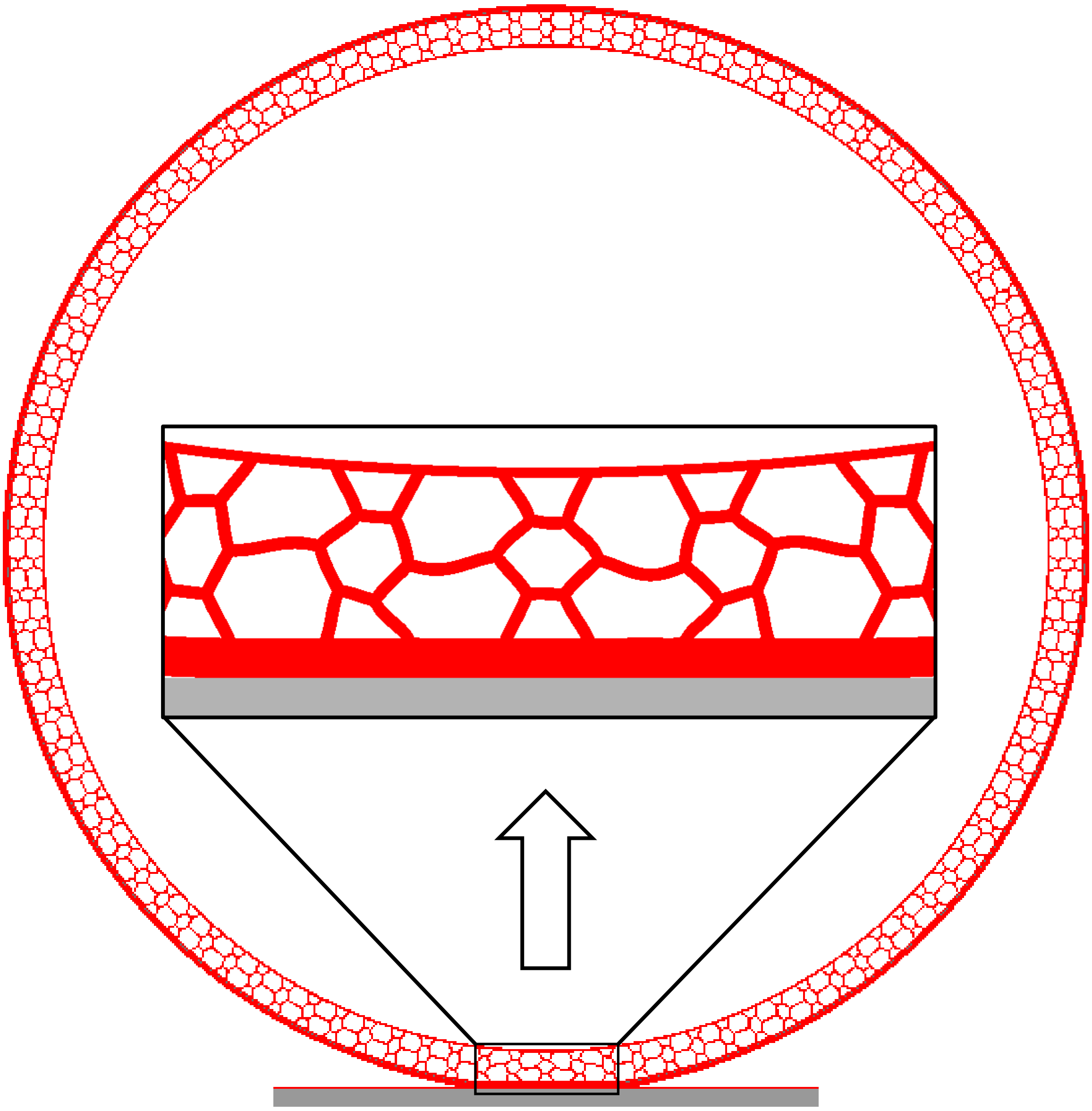


Figure 8.1 – Numerical model of the FS-NPT tuned to the design parameters which give the target vertical stiffness and lightest possible weight. Zoomed section at the contact shows the slight deformation of the honeycomb spokes.

Figure 8.2 and Figure 8.3 show stresses in the spokes over loading steps 1 and 2 respectively, with maximum exhibited stresses of 19.5 MPa and 19.4 MPa respectively. The highest stress concentrations are exhibited in the central spoke and both its neighbouring spokes around the edges where the plates connect for both load steps. The top and side spokes should be subjected to tension and shear forces respectively; however, the contour plot does not show any observable stresses at these regions which is likely due to the high stresses situated near the contact region (therefore only the lower spokes are shown).

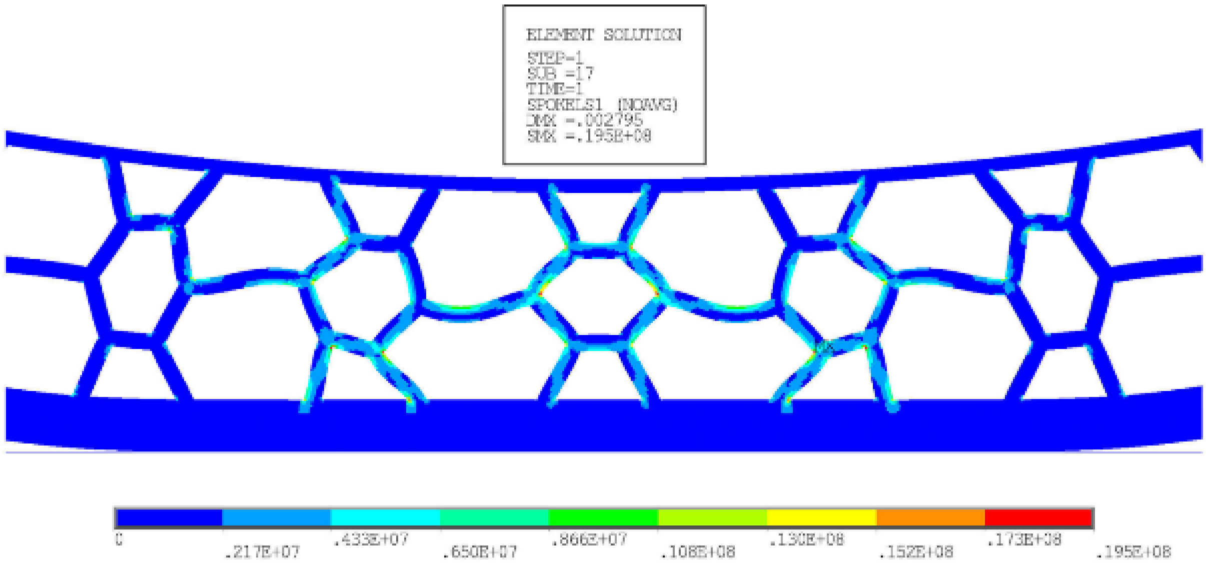


Figure 8.2 - von-Mises stress contour plot showing exhibited stresses in the spokes at the end of load step 1 (vertical load only). The box section presents details about the analysis. STEP refers to the load step number. SUB refers to the sub-step number of the respective load step. TIME refers to the simulation time, where 0 is the start of the analysis, 1 is the end of load step 1, and 2 is the end of load step 2. DMN/DMX and SMN/SMX refer to the minimum/maximum displacement and stresses in the model respectively. The colour scale shows the magnitude of stresses, where blue is minimum and red is maximum. The values of these stresses can also be seen on the scale in Pascals.

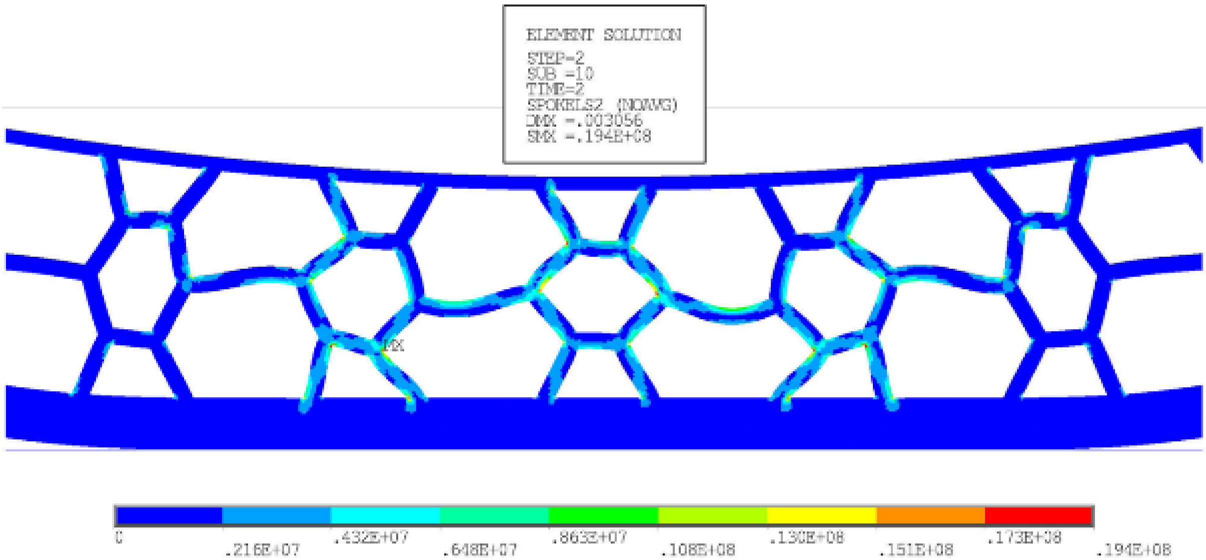


Figure 8.3 - von-Mises stress contour plot showing exhibited stresses in the spokes at the end of load step 2 (vertical and moment load).

Figure 8.4 and Figure 8.5 show stresses in the outer-ring over loading steps 1 and 2 respectively, with maximum exhibited stresses of 278 MPa and 296 MPa respectively. The highest stress concentrations are at the ring locations just above the gaps where the tyre contact to ground region ends, with the added rotation increasing the magnitude of stress by ≈6%. Bending of the ring is also highest at these locations. Lower ring stresses can be seen directly under the locations where the spoke plates meet the spoke outer layer.

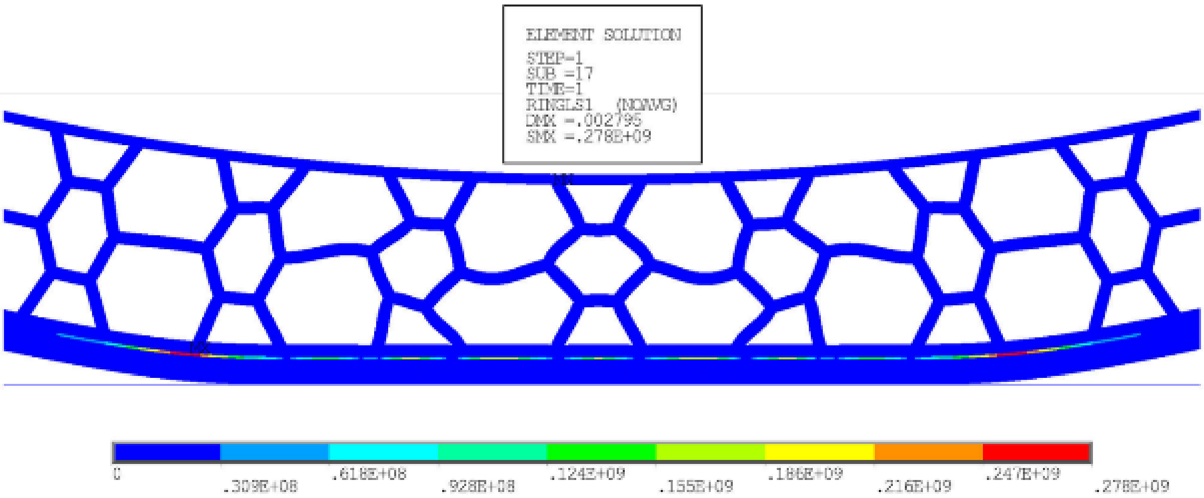


Figure 8.4 - von-Mises stress contour plot showing exhibited stresses in the outer-ring at the end of load step 1.

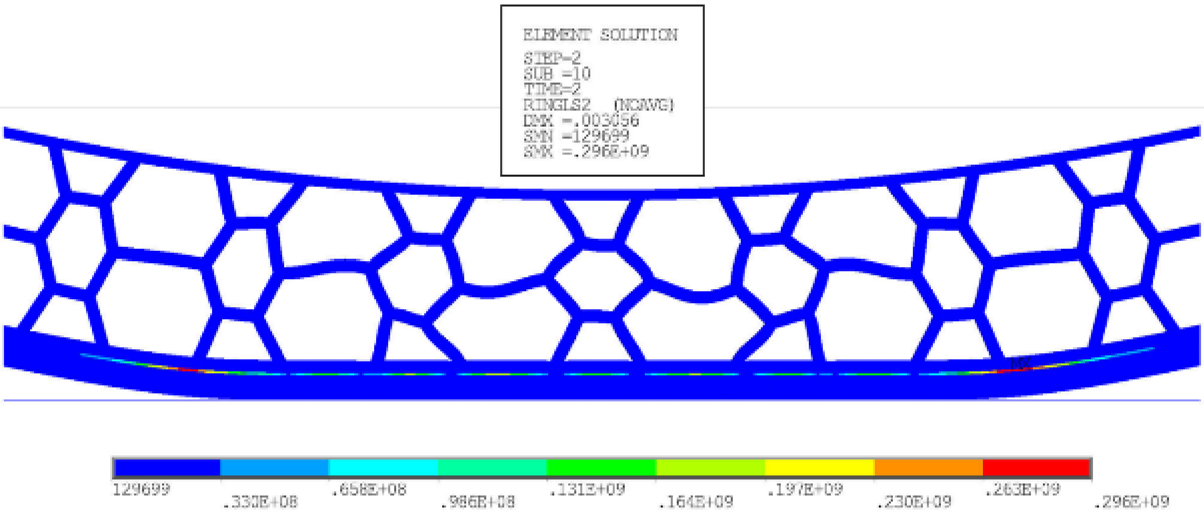


Figure 8.5 - von-Mises stress contour plot showing exhibited stresses in the outer-ring at the end of load step 2.

Figure 8.6 and Figure 8.7 show contour plots of the stresses in the tread over loading steps 1 and 2 respectively, with maximum exhibited stresses of 0.563 MPa and 0.780 MPa respectively. Maximum stress is 39% higher in load step 2, which is positioned at the base of the tread. Higher points of stress in the tread are directly below plate connections.

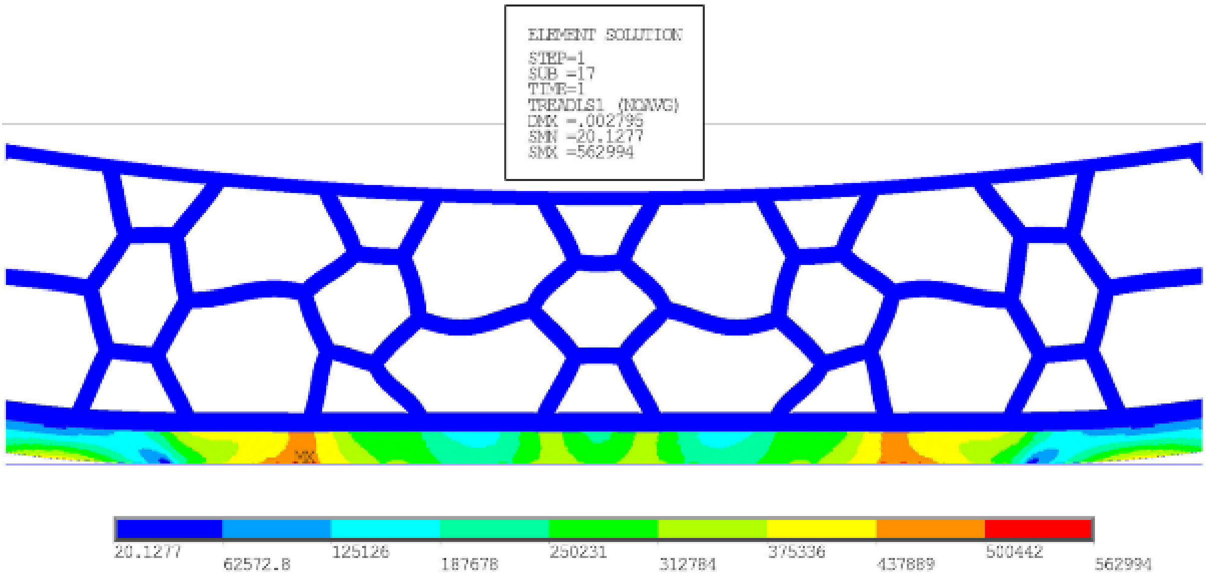


Figure 8.6 - von-Mises stress contour plot showing exhibited stresses in the tread at the end of load step 1.

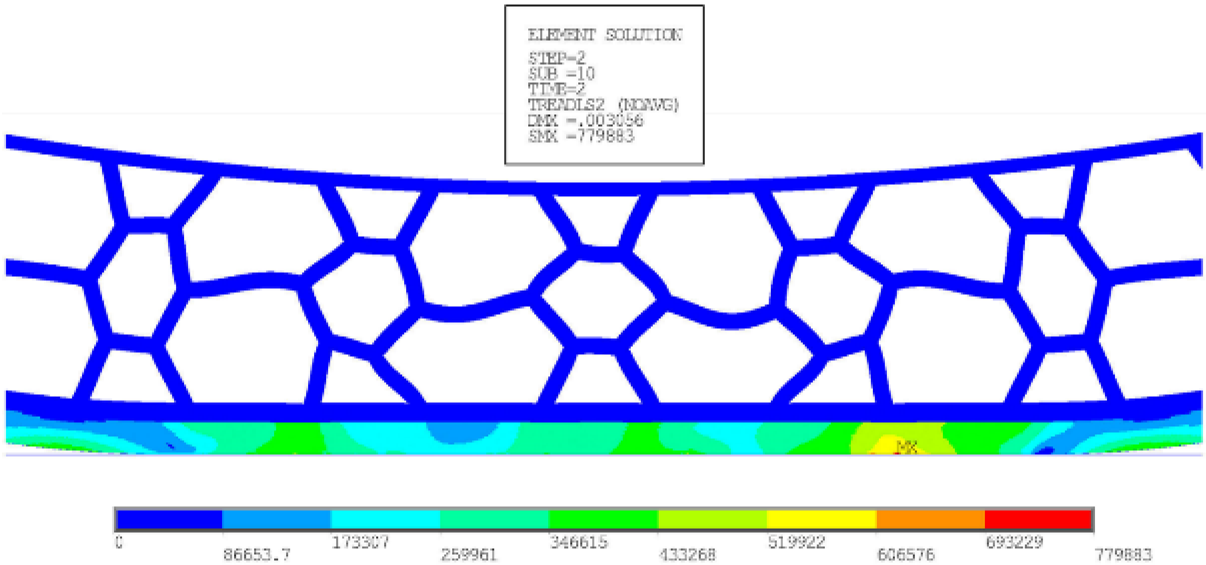


Figure 8.7 - von-Mises stress contour plot showing exhibited stresses in the tread at the end of load step 2.

8.4 Discussion

The results presented here quantify the effect of individual design parameters on tyre stiffness and maximum stresses. This is important to allow identifying a honeycomb FS-NPT design that could replicate pneumatic tyre vertical stiffness while achieving higher shear stiffness and without increasing the overall mass of the wheelchair. In addition, this analysis was conducted to assess whether a regression model can predict key outcome measures of FE modelling to enable the designing of an FS-NPT with predefined characteristics without having to run FE simulations.

8.4.1 Robust Multiple Linear Regression Model

The multiple linear regression model produced in this chapter was an improved version of the initial model presented in Chapter 7 illustrates that the initial model with the buckled scenarios excluded had a relatively large error when used to predict the outcome of the FE simulations. This error reduced and stabilised for a sample size larger than 53. Increasing sample size did not lead to significant reduction in prediction error beyond this point. For a given set of design parameters, this statistical model could predict tyre stresses with less than 10% error, and stiffnesses with less than 4% error, of which these errors are considered low enough to be acceptable. Whilst the error may have converged at 53 simulations, more simulations were added to the model to ensure this error would not decrease further. Whilst it is difficult to compare this number of simulations with literature due to the required simulations being partially dependent on what is being tested, one study suggested that 46 simulations are required for a study using 5 input parameters [112]. This is in close agreement with the convergence of this study.

This robust regression model was useful in obtaining more accurate coefficients and ‘p’ values shown in Table 8.3. This table, if compared with either Table 7.7 or Table 7.8 from the previous chapter indicates that parameters are statistically significant in affecting more outcome measures. This includes the width which according to this refined regression model, significantly influences the vertical stiffness, shear stiffness, and tread stress for L1, indicating that it was important to include in the analysis.

The percentage values in Table 8.4 calculated using the regression model were imperative in identifying the parameters required to tune the mechanical characteristics of the proposed wheelchair FS-NPT. The statistics presented here highlighted angle as a key parameter to tune vertical and shear stiffnesses. This is because it strongly influences both stiffnesses while having minimal effect on mass. Another important characteristic of angle is that it has a continuous range of possible values which makes it ideal for finetuning of stiffness (unlike spoke count which must be an integer).

Spoke count was also determined to be a very useful parameter to use to increase vertical stiffness with relatively conservative increase in mass. Indeed, when compared against other parameters, spoke count appears capable to generate the biggest stiffness gains for the same amount of added mass to the tyre. The change in vertical stiffness with changing spoke count can be seen in Graph 8.2, where the buckling point for the minimum parameter values was identified (at 106 spokes). This graph shows a non-linear curve, but a pattern can be observed with the exception of two results (102 and 105 spokes) which seem to have large stiffness changes. These outliers could be due to the way in which the load is distributed among the spokes near the contact region, or the way in which the nodes and elements are aligned when spokes are added/removed. Either way, these large changes in stiffness only occurred for scenarios which had already buckled, and so these were excluded from all analyses and should have had no effect on the results.

Using spoke count and angle as the tuning parameters enabled the production of an FS-NPT honeycomb design that was able to replicate the dimensions and vertical stiffness of a conventional pneumatic tyre, thus proving that an FS-NPT is a feasible tyre technology for wheelchairs.

Table 8.5 shows the resultant values of the FS-NPT with the targeted vertical stiffness and lowest mass, and the results from the pneumatic tyre experiment. The FS-NPT was able to achieve a mass lower than the pneumatic tyre. Pneumatic tyres are known for their low mass due to their volume mostly comprising of air, and so for a new technology to be able to replicate its vertical stiffness (which is a significant aspect of its behaviour) and be lighter in weight suggests that FS-NPTs are a good candidate technology for wheelchairs. Reduced mass also contributes to propulsion efficiency; a heavier tyre is harder to turn, and also increases difficulty during transit, so the tyre should be as lightweight as possible.

Future work could involve the use of a machine learning algorithm, such as a multi-layer perceptron regressor, which can identify combinations of parameters that will cause buckling, allowing them to be excluded, or even predict the behaviour of buckling, allowing it to be potentially utilised. For example, buckling causes large deformation in the spokes, which could absorb the large forces that are usually transmitted to the user when a wheelchair dismounts a kerb, thus improving ride quality. Being able to reduce or even replace fully FE modelling for tyre behaviour tuning will open the way for the application of this technology outside research to directly adapt FS-NPT designs to the specific needs of individual users. For example, the statistical model could be redesigned to produce a specific design with the optimal stiffness/weight/durability for an individual user when their weight/preferences are supplied (such as a combination of design parameters which ensures the spokes deform for comfort but do not buckle under their weight). This unique capacity for personalisation however will have to be complimented with a flexible but robust manufacturing process. Based on the work presented here, work on developing a unique manufacturing process can now commence.

8.4.2 Limitations

Table 8.2 shows that the vertical stiffness of the ten randomly generated simulations ranged from 155 to 253 kN/m. The regression model was therefore likely to be as accurate as the percentage error that is stated in Table 8.2 within this range of vertical stiffnesses (as the error was assessed using these ten simulations). As the target vertical stiffness was outside of this range (139 kN/m), this could explain why the regression model had a much higher error of 15% (compared to the 2% stated in Table 8.2) as this area of stiffness is where non-linear behaviour begins to occur due to buckling of the spokes. The buckling threshold was previously determined to be 122 kN/m, and simulations below this stiffness had buckled. However, buckling cannot be determined with this model through assessment of the design parameters alone as it assumes linear relationship between design parameters and outcome measures. This linear relationship is disrupted by buckling. Building on the present study, further FE analyses are required to quantify the specific combination of design parameters that will or will not cause buckling in the spokes.

8.5 Conclusion

The objective of this chapter was to determine the honeycomb design parameters that can tune the tyre's mechanical behaviour. These parameters were then used to achieve the same vertical stiffness as the baseline pneumatic tyre. The main findings were:

- A multiple linear regression model can be used to identify the design parameters required to tune the mechanical behaviour of an FS-NPT.
- A wheelchair FS-NPT is capable of replicating current wheelchair tyre technology, specifically the vertical stiffness, meaning it can provide similar suspension properties to pneumatic tyres and proving it to be a feasible technology.
- Spoke count and angle are the optimal parameters that can be used to tune the FS-NPT to obtain a specific vertical stiffness (pneumatic tyre target stiffness) with the lowest possible mass.

An FS-NPT can achieve a lower mass than a standard pneumatic wheelchair tyre. which can contribute to increased wheeling efficiency and ease of transportation.

Chapter 9: Discussion

9.1 Chapter Overview

This chapter collates the findings from previous chapters and makes discussions in the context of the objectives. At this point in the thesis, the first two objectives were considered to have been met based on the work of previous chapters; key milestones of these objectives are presented and discussed in the subsequent sections to clearly show where and how these objectives were met. The third and final objective required combining and analysing the work from multiple chapters to explore whether FS-NPTs can provide potential improvements to wheelchair users' experience. This objective has not been assessed in any part of the thesis up to this point (contrary to objectives 1 and 2) and is fully discussed in this chapter (specifically section 9.4).

9.2 Predicting the Mechanical Behaviour of FS-NPTs

The first objective of this thesis was to develop a methodology to predict the mechanical behaviour of an FS-NPT based on the design of its spokes. The key chapters involved in meeting this objective were Chapter 5, Chapter 6, and Chapter 7. More specifically, the combination of FS-NPT literature knowledge, finite element modelling, and experimental testing contributed towards the first operational numerical model of an FS-NPT designed for wheelchairs, that was capable of predicting the mechanical response to typical loading scenarios. Investigating literature as an initial step to this objective not only conveyed that a wheelchair FS-NPT has never before been explored but also provided the foundational knowledge in the design choice (honeycomb) and finite element methods taken forward to produce a working numerical model. The investigation of different element types was a critical step in ensuring that the results of the numerical model closely aligned with experimental findings, with a maximum error of 3% between thickness ranges of 1.5mm to 2mm (Table 6.1). The final produced numerical model (on Mechanical APDL) was capable of predicting important mechanical behaviour such as stresses, strains, deformations etc., and the geometry (including the spokes) could be altered to view the change in mechanical response. This robust numerical model was therefore capable of predicting the mechanical behaviour of a wheelchair FS-NPT based on the design of its spokes, and objective 1 was considered met at this stage (Chapter 7).

In relation to the thesis, meeting this objective resulted in a working tool that could be used to test whether FS-NPTs can attain mechanical behaviour similar to conventional wheelchair tyres. As a stand-alone numerical model, this tool can be used to predict the mechanical behaviour of varied spoke structures (such as radial, triangle spokes etc.), it can be used to test other materials that may be viable for wheelchair tyres and could even test different types of tyres provided that the correct modelling strategy is used to accommodate for the varied dimensions (to ensure results are accurate). Numerical models of FS-NPTs that are capable of predicting mechanical behaviour are currently available in literature (see Chapter 5), but only approximately 20% of studies in literature validated their findings with experimental testing, and 70% designed FS-NPTs for automotive applications. There is no evidence of FS-NPTs having been designed/investigated for wheelchair applications.

9.3 Replicating Wheelchair Mechanical Characteristics in FS-NPTs

The second objective of this thesis was to test whether FS-NPTs can replicate the mechanical characteristics of existing wheelchair tyres. The key chapters involved in meeting this objective were Chapter 4, Chapter 7, and Chapter 8. The experimental testing of conventional wheelchair tyre technology, combined with the production of a validated FE model and tuning method allowed the development of a numerical concept that can replicate important tyre characteristics of conventional wheelchair tyre technology. The methods of measuring wheelchair pneumatic tyre stiffnesses led to repeatability within the results, proving the reliability of the testing methods and yielding an accurate estimation of the baseline behaviour of this tyre type when compared with literature (necessary for FS-NPT replication). The employment of Taguchi methods combined with statistical modelling utilising FE data of FS-NPTs of various spoke geometry led to the creation of a statistical model capable of predicting the mechanical behaviour of an FS-NPT without the need for FE simulations. The percentage error of this model was less than 4% in predicting important tyre stiffnesses, but it was only valid within a limited range of parameter values. The statistical model was utilised and combined with several FE simulations (to ensure accuracy), which led to the development of a wheelchair FS-NPT numerical model that had the same vertical stiffness as the wheelchair pneumatic tyre, and objective 2 was considered met at this stage.

The vertical stiffness was deemed the tyre characteristic for an FS-NPT to replicate for feasibility as pneumatic tyres inflated to recommended pressure generally have good absorption properties (and this is a requirement for an FS-NPT to be competitive with current technology). User comfort (from good absorption properties) was shown to be of high importance to wheelchair users in both existing literature and the questionnaire findings (Chapter 3), highlighting the feasibility of this tyre in meeting crucial user needs. Replicating mechanical characteristics of conventional technology is common practice in literature to suggest viability of a new tyre technology, with specific studies using vertical stiffness as the main characteristic for comparison [83,113]. This procedure has never been attempted or successfully conducted for wheelchair FS-NPTs in existing literature. This work highlights the applicability of FS-NPTs in wheelchairs, which could open the way to further research in this area to explore its potential use and value in wheelchair applications.

9.4 Potential Improvements of FS-NPTs for Wheelchair Users

The third and final objective of this thesis was to explore the potential improvements to user experience that wheelchair FS-NPTs could offer. The key chapters involved in meeting this objective were Chapter 3 and Chapter 8.

The questionnaire in Chapter 3 highlighted that manual wheelchair users would like their tyres to have high wheeling efficiency, shock/vibration absorption, low mass, high manoeuvrability, and high durability (according to question 40b). It also highlighted that most users' current tyres do not possess these desirable characteristics (question 41b). These findings indicate that a new tyre that possesses aforementioned properties could be considered an improvement to current tyre technology through providing users with additional benefits that they themselves have deemed desirable.

The FS-NPT was able to replicate the vertical stiffness of conventional wheelchair technology in Chapter 7. In Chapter 8, the FS-NPT had a shear stiffness substantially higher than the pneumatic tyre (2078%). Pneumatic tyres are also known for having high wheeling efficiency (higher than the main alternative solid non-pneumatic tyres)[6], and so this again suggests that FS-NPTs are a good candidate technology. The shear stiffness values in Table 8.2 also show a wide range of stiffnesses that appear to be mostly independent from vertical stiffness values, highlighting the potential for tuning to optimum comfort and wheeling efficiency.

The stresses that the FS-NPT exhibits are closely related to the durability of the tyre. Typically, if the stresses are below the yield point of the material, durability should be high. However, regarding the stresses in the spokes, TPU95 is a complex polymer which does not have a specific yield point [106]. This was also confirmed in Chapter 6 when the stress-strain data of TPU95 was calculated from the mechanical testing results and found to be non-linear. The stress at breaking point can be used as the material should not have undergone plastic deformation. This stress was approximately 24 MPa [106]. The maximum stresses exhibited in the spokes were approximately 19 MPa for both load steps which is below breaking point with a safety factor of 1.26. For the spokes only, these stress values could potentially be exaggerated as the spoke design of the numerical models have perfectly sharp corners which can cause high stress concentrations. In reality, manufactured components will have tolerances and smoother corners and thus lower stresses. Averaging the stress values in Mechanical APDL which can reduce peak stresses caused by geometry equates to stress values of 12.8 MPa and 13.1 MPa for load steps 1 and 2 respectively, which are likely closer to the actual peak stresses in the spokes (increasing the safety factor to 1.83). The peak stresses of the ring and tread are likely be more accurate due to their more simplistic geometry. The rubber used for the tread is also a non-linear material and its yield point is not absolute. However, according to literature, rubber has a tensile strength of 16.5 MPa to 21.2 MPa [114], and the maximum stress observed in these analyses is less than 1 MPa, indicating that the rubber will possess high durability. The highest stresses in the whole tyre are exhibited in the outer-ring, with a maximum of 296 MPa in load-step 2 acting towards the edge of the contact region. The outer-ring is made from the strongest material (AISI 4340 steel alloy) of the tyre which has an average yield strength of 826 MPa, but it is dependent on treatment [115], and so it has a sufficient factor of safety and will therefore be durable. The average fatigue endurance limit for this material is 574.3 MPa [116], and amplitude stresses below this value are unlikely to fail due to cyclic loading. Therefore, this tyre should not fail due to fatigue as its maximum stress is below the endurance limit. The components of the FS-NPT exhibit stresses below their yield points, indicating that the tyre will have good durability, promoting longevity and decreasing the occurrence of tyre replacements for users. Tyre replacement may need manufacturer support due to a potentially complex mounting procedure, but this is sometimes the case for solid/pneumatic tyres depending on the user's ability,

Another benefit of this tyre is its puncture-proof ability. Question 38 of the questionnaire indicated that most users found it 'extremely difficult' to replace their tyres after the occurrence of a puncture. This prevents users from becoming stranded due to a punctured tyre which requires increased energy to propel and is also financially beneficial as a new tyre is sometimes needed when a pneumatic tyre is punctured, or patches/sealants are used which are not a viable permanent solution. However, question 37 of the questionnaire highlighted that only 18% of participants had a puncture in the last 12 months which does not appear to be a substantial amount. A portion of these respondents had puncture resistant tyres and would have answered zero for this question. These respondents using puncture-proof tyres may be doing so as they have had a puncture in the past and then transitioned from pneumatic to solid (or tyre inserts/foam). Also, the participants that use pneumatic tyres may avoid certain terrains or environments to mitigate the risk of punctures from previous experiences (which could relate to reduced inclusivity/independence). Additionally, being puncture-proof in combination with good durability promotes the longevity of this tyre, which could make it a cost-effective product, despite likely having an initially high upfront cost.

This FS-NPT is considered to be a low maintenance tyre as it does not require pressure inflation. Question 35 of the questionnaire indicated that most users found it ‘difficult’ to inflate their tyres, and this tyre eliminates the need for this.

The above discussion points outline the potential improvements that FS-NPTs can offer to wheelchair users, which include higher wheeling efficiency, better durability, puncture resistance, and lower maintenance. These improvements are based on the questionnaire findings of Chapter 3 which provided insight into wheelchair users’ needs regarding their tyres which was previously unavailable in literature. These improvements to wheelchair users could promote awareness of this technology in the research area which could lead to the development and implementation of this technology, to ultimately improve the quality of life of wheelchair users. Objective 3 and thus all objectives of the thesis were considered met at this stage.

9.5 Limitations

The numerical model of the FS-NPT developed in Chapter 7 was validated based on a honeycomb design with specific dimensions. These dimensions were altered in Chapter 8, and any deviation from the geometry of the validated model could cause model inaccuracies. These inaccuracies are assumed to be negligible, but the tyre should be manufactured and mechanically tested to confirm that these values are indeed true.

Replicating the vertical stiffness of existing wheelchair tyre technology in FS-NPTs is a valid method to assess the feasibility of tyre technology, and vertical stiffness is closely related to comfort, meaning that the FS-NPT should have similar comfort levels to conventional tyre technology. However, the vertical stiffness was only measured under static conditions, and a time-dependent response would give more insight into the dampening and shock absorption abilities of the tyre. Therefore, dynamic simulations should be carried out to confirm and further assess the potential levels of comfort that wheelchair FS-NPTs can offer.

The regression model developed in Chapter 8 is a useful tool to use to minimise the number of simulations required to obtain specific results. Fine tuning with FE simulations may still be needed to obtain tyre results or parameter dimensions with high accuracy, but this significantly reduces the trial and error usually needed and therefore significantly reduces computational time.

Material selection will be key in this development process towards new products and services for wheelchair users. The material used in the simulations (TPU95A) was chosen due to its similarity to the spoke materials found in literature and its availability for rapid prototyping. Whilst this material was successfully used to validate FE models which in turn proved the feasibility of an FS-NPT, its high flexibility caused the structure to buckle undesirably with combinations of parameters close to the target vertical stiffness. Stiffer materials with similar density could be explored in the future to increase the range of scenarios close to the vertical stiffness and potentially provide combinations of parameters with a lower mass. Other drawbacks of TPU include low resistances to creep, moisture, UV light, and fatigue cyclic loading [117,118]. A person sat stationary in their wheelchair for a long time may cause buckling of the spokes due to prolonged stress (which is similar to flat spots on motorbike pneumatic tyres during winter storage). When the wheelchair is unloaded, it is assumed that the weight of the wheelchair itself will have little effect on the spokes. TPU can also be prone to environmental damage such as prolonged exposure to sunlight and rain which can negatively influence the mechanical properties. Finally, fatigue failure is common in cyclic loading conditions such as a rolling tyre, and TPU additively manufactured via fused deposition modelling is likely to undergo crack propagation between fused layers during operation. However, materials already used in automotive applications of FS-NPTs appear to be better candidates to be explored during future work. These materials are significantly stiffer, stronger, and are highly resistant to the aforementioned disadvantages due to their robust manufacturing process (injection moulding), and additional treatments such as curing to improve mechanical performance and resistance to failure [118,119]. Transitioning to such materials maximises the chances of developing a durable and lightweight wheelchair tyre.

The production time and cost of FS-NPTs will likely be high compared to conventional wheelchair tyre technology as pneumatic tyres are mass produced. However, the suggested longevity of these tyres means longer intervals between tyre changes which is cost effective, and literature trends highlight growing popularity of these tyres which could result in near-future mass production to bring cost and production time down.

Chapter 10: Conclusion

10.1 Key Findings

The motivation of this PhD thesis was to improve the quality of life of manual wheelchair users through the development of flexible spoke non-pneumatic tyres. In this project, three objectives were established to clarify the purpose of the project and the work that is to be achieved by the end. These objectives were outlined in Chapter 9 where the findings from relevant chapters were collated and discussed to illustrate where and how they have been met. The key findings from this thesis are:

- Questionnaire evidence suggests that conventional manual wheelchair tyres (pneumatic/solid) do not meet the needs of the majority of its users.
- FS-NPTs can replicate the mechanical characteristics of conventional manual wheelchair tyre technology (specifically vertical stiffness), suggesting this tyre technology to be feasible for manual wheelchairs.
- Based on wheelchair user feedback on the assessment of their needs, FS-NPTs can offer improvements to manual wheelchair users over conventional tyre technology. These improvements correspond to a tyre that is easier for the user to turn, lasts longer, cannot be punctured, and requires minimal maintenance.

These findings strongly suggest that FS-NPTs are a good candidate technology for wheelchairs. The work of this thesis led to the production of an FS-NPT concept that can provide improvements over current tyre technology according to wheelchair users themselves. The key findings of this work have been published in high impact academic journals which contribute to the research areas of wheelchair tyres and FS-NPT technology (Appendix D). These contributions can lead to the development of research in these areas and could enable the adoption of new technology which can positively impact the quality of life of wheelchair users. However, the findings of this work are based on the developed FS-NPT concept. The procurement of materials and the manufacturing of FS-NPTs on a full-scale level will likely be significant in influencing financial cost and production time, which could act as a barrier for consumer adoption. This technology therefore requires further investigation before it can be proved that these tyres are an alternative and a potentially superior wheelchair tyre technology.

This thesis adopted a mixed methods approach in the investigations and research of wheelchair user needs and FS-NPTs. Acquiring feedback from wheelchair users meant that the FS-NPT concept could be analysed not just on mechanical behaviour that seemed favourable from a mechanical engineering perspective, but behaviour that wheelchair users themselves have deemed desirable. Integrating consumer feedback into the development process of any product (or concept) should not be ignored and is crucial in developing a product/technology that is optimal for the target audience. Therefore, utilising this approach is a major strength of the thesis which supports the key findings presented.

Overall, this work has explored the potential use and value of FS-NPTs in wheelchair applications and is a major foundation to improving the quality of life of wheelchair users.

10.2 Contribution to Knowledge and Novelty

Contribution 1 – FS-NPTs appear to be good candidates for wheelchairs.

The main contribution to knowledge of this project was the creation of an FS-NPT concept that provides improvements over current wheelchair tyre technology. This tyre was able to replicate the vertical stiffness of a pneumatic tyre which is known for having good suspension and therefore good user comfort. It had significantly higher shear stiffness than the pneumatic tyre, of which the main benefit of this is improved wheeling efficiency for the user. This tyre was able to achieve a mass lower than the pneumatic tyre, contributing to its wheeling efficiency and highlighting its high performance-to-weight ratio. Additional benefits, including good durability, was shown to be attainable through low stress concentrations in the FE results, and other benefits including low maintenance, and puncture-resistance are inherent characteristics of airless tyres This tyre can provide the benefits of the main two types of current wheelchair tyres, whilst possessing none of the disadvantages. Demonstrating that FS-NPTs are a viable competing technology opens the way for new avenues of research and future development that could provide wheelchair users with tyres that are comfortable, mitigate user injury risk and overexertion, and thus promote user independence and inclusivity.

Contribution 2 – In-depth wheelchair user feedback regarding their views and experiences.

A target of this project was to determine the needs of wheelchair users in general and in terms of their tyres. Whilst there are numerous studies and questionnaires on wheelchair user satisfaction regarding their whole wheelchair, research on their satisfaction when it comes to wheelchair tyres was scarce. In some studies, tyres were mentioned but in a very brief manner and were not the main concern of any project regarding what users' desire from their tyres. The present work highlighted that information on the tyre characteristics that wheelchair users currently have and would want their ideal tyres to have, was not available in literature. To fill this gap, a questionnaire was created (Chapter 3) which asked participants about their tyres, specifically the characteristics that they currently have and what their ideal tyres would have (and many other questions on their wheelchair, mobility, and their tyres).

This knowledge proved invaluable to this project as it was required to determine the mechanical behaviour necessary to produce an effective FS-NPT. This questionnaire can also serve future research and development to improve wheelchair tyre technology beyond FS-NPTs.

Contribution 3 – A new optimum finite element modelling strategy for modelling FS-NPTs of various dimensions.

The idea of an FS-NPT for a wheelchair was first proposed in this project and has never been tested or used according to literature. Whilst there was an abundance of studies that investigated FS-NPTs via FE methods, the majority of these were based on automotive applications and there were no studies available in literature that tested FS-NPTs that had similar dimensions to conventional manual wheelchair tyres. There was therefore a lack of knowledge concerning FS-NPTs of varied dimensions, and a general lack of knowledge for modelling honeycomb spoke structures, and this knowledge was required to progress the project and provide accurate numerical data. Due to the honeycomb wheelchair FS-NPTs having an intricate design when scaled to manual wheelchair tyre dimensions, the modelling strategy was not straight forward. It was discovered that the spoke thickness-to-height ratio being largely different to any other application meant that element type choice was significant in ensuring the results were accurate. To determine the optimum elements, mechanical testing was conducted on 3D printed spoke segments, and these segments were replicated numerically, and three element types were trialled to determine the type with the highest accuracy. Due to the element type being largely dependent on the thickness-to-height ratio, different spoke thicknesses were tested. 3D shell elements were discovered to be most suitable for designs with thickness-to-height ratios of 1/18 and below, whilst 2D plane elements were discovered to be most suitable for designs with thickness-to-height ratios of 1/12 and above. This creation of knowledge will be extremely useful for future research in modelling non-pneumatic wheelchair tyres with flexible spokes and it also greatly contributes to other FS-NPT applications of similar and varied dimensions (shedding light on the different modelling strategies that may be needed for different dimensioned FS-NPTs). This new knowledge will also aid in accurately modelling honeycomb spoke structures beyond the specific application of this thesis.

10.3 Recommendations & Future Work

This project concluded with an optimum FS-NPT design that has the potential to improve comfort and energy efficiency of manual wheelchairs. To expand on the work done here, more advanced FE tests could be carried out, involving dynamic testing. This would allow simulations of a wheelchair FS-NPT during propulsion, and different dynamic scenarios could be tested such as steady-state rolling, rolling over an obstacle, rolling over rough terrain etc. This is more representative of real-life situations that wheelchair users face every day and would help further understand the tyre behaviour and may influence some of the design parameters which deem it optimum. It would also be useful to measure tyre characteristics that wheelchair users deemed favourable, namely manoeuvrability and durability to explore if FS-NPTs can provide further benefits to users.

For future work, this optimum FS-NPT could be manufactured as a whole tyre and mechanically tested for vertical stiffness, shear stiffness, and mass to determine the concluded behaviour of this FS-NPT concept is accurate. Furthermore, the manufactured FS-NPTs can be attached to a wheelchair (onto the wheel rim) and laboratory tests can be conducted and directly compared with the pneumatic tyre experiment.

In-vivo testing is a method that can be conducted in the future. Wheelchair users can be involved in a series of tests which include testing pneumatic tyres over different terrain and obstacles, and then performing the same test on a wheelchair with optimally designed and manufactured FS-NPTs. At the end of these experiments, users can rate their experience and satisfaction with both tyres to determine if FS-NPTs are indeed a better candidate than pneumatic wheelchair tyres. This would further the technology readiness level and bring this concept one step closer to actual implementation and improving the quality of life of wheelchair users.

Due to FS-NPTs showing high performance characteristics over current tyre technology, they may be useful for athletes who use performance wheelchairs for sports and competitions. These tyres showed promising shear stiffness results which reduces the energy loss during propulsion which could allow for potential increases in speed, or less frequent propulsion required. Furthermore, due to their high tuning capabilities, these tyres could be tuned very specifically to an individual to maximise the performance of the wheelchair based on the person's characteristics and preferences.

These tyres are also applicable to other low speed applications such as bicycles. The dimensions of bicycle tyres are very similar to manual wheelchair tyres, and so the work done on the accurate modelling and simulating of these non-pneumatic tyres can act as a foundation for future research in this area. The requirements of these tyres will likely differ drastically to wheelchairs and will need separate investigations.

The questionnaire can be used to assess the needs of electric wheelchair users which can inform the designs of FS-NPTs suitable for motorised wheelchairs. Whilst these tyres were considered more useful to manual wheelchair users, they could still provide wheelchair users with additional benefits and should be explored.

This PhD has developed a concept of a wheelchair FS-NPT that has enhanced behaviour over current tyre technology (Technology Readiness Level 2). The next step would be to manufacture and test this tyre, validating this concept. This project aligns with the goals of EPSRC and will contribute to delivering impactful research and addressing significant societal challenges by improving accessibility and inclusivity for wheelchair users.

Beyond this, successful validation of basic science and key concepts of a wheelchair FS-NPT in the laboratory (Technology Readiness Level 3) will unlock access to InnovateUK funding. InnovateUK's focus on the development of new products/services is a perfect alignment with the aims and goals of this project. Moreover, the evidence about the feasibility and the potential benefits of a wheelchair FS-NPT will enable effective engagement with industry and enhance the chances for attracting direct investment.

10.4 Closing Remarks

The work of this PhD and thesis have been a major part of my life for the last four years. There have been many setbacks, from jammed printer nozzles ruining a large batch of 3D prints, to solving 12+ hour finite element simulations that crash at 95% completion. Through perseverance came unforgettable successes, in particular, reaching the questionnaire recruitment goal and of course finalising the design of a feasible wheelchair tyre. Ultimately, it has been an enjoyable and progressive experience and an experience I will likely never have again.

A crucial part of this experience was the participation of wheelchair users. Involving end users in my research was important to ensure that the work I produced was what the target audience actually needed. It's easy to get caught up in the engineering side of things and lose focus on what is really important. Feedback from the questionnaire enlightened me on some of the real-world problems that wheelchair users are exposed to, and it was different from the things I'd read in literature. They weren't just findings or statistics; they were real people telling me their real problems. This deepened my passion for the project and made it more about them than myself, and what a difference I could be making to so many people rather than just focusing on furthering my academic journey. This is why it is imperative to take this further in the future and really collaborate with wheelchair users throughout the research process. I hope that if I continue in this avenue of work, I will stay true to this to ensure that the work is the best it can be for the people who need it.

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Appendices

Appendix A – Wheelchair User Needs Questionnaire

Wheelchair User Questionnaire:

Wheelchair User Questionnaire (UK)

This questionnaire aims to discover the views and experiences of wheelchair users. By taking part in this questionnaire, you are helping to further research into this area of study. This research could help in the development of novel designs which in future could improve wheelchair functionality.

* Required

INFORMATION SHEET (1/3)

Project Reference Number: [SU_21_059]

Title of Study: *Assessment of wheelchair user needs.*

I would like to invite you to participate in this research questionnaire. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like more information.

What is the purpose of the questionnaire?

The purpose of this questionnaire is to gather the thoughts and experiences of wheelchair users to determine the current functionalities of wheelchairs.

Why have I been invited to take part?

You have been identified to participate because you are a wheelchair user and you live in the UK.

What will happen if I take part?

If you consent, your next steps will be to answer the questions in the questionnaire that are applicable to you. The results collected for this study will be kept confidential and the data will remain anonymous throughout.

INFORMATION SHEET (2/3)

Do I have to take part?

Participation is completely voluntary. You should only take part if you want to and choosing not to take part will not disadvantage you in anyway. Once you have read the information sheet, please contact us if you have any questions that will help you make a decision about taking part. If you decide to take part, we will ask you to sign a consent form.

What are the possible risks of taking part?

There are no possible risks of taking part in this study.

What are the possible benefits of taking part?

There are no intended benefits for you taking part in this study. The improvement of wheelchairs is a long-term goal of the project however, and so helping to address the problems with wheelchairs should aid in the project's development and success.

Data handling and confidentiality

Your data will be processed in accordance with the data protection law and will comply with the General Data Protection Regulation 2016 (GDPR).

Data Protection Statement

Your data will be processed in accordance with the General Data Protection Regulation 2016 (GDPR). The data controller for this project will be Staffordshire University. The University will process your personal data for the purpose of the research outlined above. The legal basis for processing your personal data for research purposes under GDPR is a 'task in the public interest'. You can provide your consent for the use of your personal data in this study by completing the consent form below.

You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation. You also have other rights including right of correction, erasure, objection, and data portability. Questions, comments and requests about your personal data can also be sent to the Staffordshire University Date Protection Officer. If you wish to lodge a complaint with the Information Commissioner's Office, please visit: www.ico.org.uk

INFORMATION SHEET (3/3)

What if I change my mind about taking part?

You are free to withdraw at any point of the questionnaire, without having to give a reason. Withdrawing from the questionnaire will not affect you in any way. You can decide to withdraw your consent to be contacted again at any point. If you choose to withdraw from the study, we will not retain any information that you have provided us as part of this study.

How is the project being funded?

The questionnaire is part of a PhD studentship which is partly funded by the European Regional Development Fund.

What will happen to the results of the study?

All personal information will be kept confidential and the data we collect from you will remain anonymous throughout. Information will be kept on a password protected computer, and only the researcher/supervisors will have access to this information. The data will be used for research purposes and data will be published in either a report or a paper. If you need individual results, we can release these to you once the analysis has been completed. If you want to know more about the study findings as a whole, you can contact the researcher (see contact details below).

Who should I contact for further information or if something goes wrong?

If you have any questions or require more information about this questionnaire, please contact me or my supervisor using the following contact details:

Researcher Name: Otis Wyatt
Email: otis.wyatt@research.staffs.ac.uk

Supervisor Name: Dr Panagiotis Chatzistergos
Email: panagiotis.chatzistergos@staffs.ac.uk

If this study had harmed you in any way or if you wish to make a complaint about the conduct of the study, you can contact the study supervisor or the Chair of the Staffordshire University Ethics Committee for further advice and information:

Name: Tim Horne Email: Tim.horne@staffs.ac.uk Telephone: +44 (0)1782 295722
Address: Cadman Building, Staffordshire University, College Road, Stoke-on-Trent, ST4 2DE

Thank you for reading this information sheet and for considering taking part in this research.

CONSENT FORM

1. I have read and understood the information sheet. *

◯ Yes

2. I consent to being contacted by email/telephone for the purpose of the project. *

◯ Yes

3. I have been given the opportunity to ask questions, and I have had any questions answered satisfactorily. *

◯ Yes

4. I understand that my participation in this questionnaire is entirely voluntary and that I can withdraw at any time without having to give an explanation. *

◯ Yes

5. I consent that data collected could be used for publication in scientific journals or could be presented in scientific forums (conferences, seminars, workshops) or can be used for teaching purposes and understand that all data will be presented anonymously.
*

◯ Yes

6. I agree that data will only be used for this project, although the data may also be audited for quality control purposes.
*

◯ Yes

7. I understand that all data will be sorted safely on a password protected computer (electronic data) or locked away securely (hard copies of data) for 10 years before being destroyed.
*

◯ Yes

8. I hereby give consent to take part in this questionnaire.
*

◯ Yes

Information about you.

All questions require an answer. Please choose "prefer not to say" or "N/a" if necessary.

9. What is your age? If you prefer not to say, please enter N/a. *

10. What is your gender? *

- Male
- Female
- Non-binary
- Prefer not to say
- Other

11. What is your weight in kilograms? If you prefer not to say, please enter N/a. *

12. How would you describe the level of accessibility in the area that you live?

(e.g. are the pavements wide enough for your wheelchair? Can you access shops? Do you require assistance due to lack of ramps? etc.) *

- ◯ Inaccessible
- ◯ Very limited accessibility
- ◯ Moderately accessible
- ◯ Widely accessible
- ◯ I don't know / Prefer not to say

13. From the options below, which best describes the area where you live? *

- ◯ City
- ◯ Town
- ◯ Village
- ◯ Countryside
- ◯ Prefer not to say
- ◯ Other

14. What are the letters at the beginning of your postcode? (e.g. if your postcode begins with ST5 put ST, if L7 put L). If you prefer not to say, please enter N/a. *

Your wheelchair.

15. How many years have you been using a wheelchair? If you prefer not to say, please enter N/a. *

16. Which condition(s) caused your need for using a wheelchair? *

- [ ] Amputation
- [ ] Multiple Sclerosis
- [ ] Muscular Dystrophy
- [ ] Spina Bifida
- [ ] Spinal Injury
- [ ] Stroke
- [ ] Polio
- [ ] Prefer not to say
- [ ] Other

17. Is the main wheelchair you are currently using custom-made to suit your requirements? *

- ◯ Yes
- ◯ No
- ◯ I don't know / Prefer not to say

18. Have you made any adjustments to the wheelchair seat after receiving this wheelchair? *

- ◯ Yes
- ◯ No
- ◯ I don't know / Prefer not to say

19. If you have made adjustments to the seat, what specific adjustments have you made? *

- ☐ I have not made any adjustments
- ☐ Adjusted the height
- ☐ Adjusted forward/backward
- ☐ Adjusted the angle
- ☐ Changed the cushion
- ☐ Other

20. Have you made any adjustments to the backrest after receiving your wheelchair? *

- ◯ Yes
- ◯ No
- ◯ I don't know / Prefer not to say

21. If you have made adjustments to the backrest, what specific adjustments have you made? *

- ☐ I have not made any adjustments
- ☐ Adjusted the height
- ☐ Adjusted foward/backward
- ☐ Adjusted the angle
- ☐ Other

22. Which type of wheelchair do you currently use? *

- ◯ Manual (including power assisted)
- ◯ Electric
- ◯ Both

23. Have you previously used a manual AND electric wheelchair for at least 3 months each? *

◯ Yes

◯ No

24. Which is your preferred wheelchair type? *

◯ Manual (including power assisted)

◯ Electric

◯ I don't have a preference

◯ Not applicable (I only have experience with one type of wheelchair)

25. If you have a preference on the type of wheelchair, what is/are the reason(s) for this? *

☐ Enables me to move with less exertion

☐ More comfortable

☐ Not applicable

☐ Lower cost

☐ Reduced maintenance

☐ Better manoeuvrability

☐ Other

26. Do you feel that your needs are different for a manual wheelchair compared to an electric wheelchair? *

- ◯ Yes
- ◯ No
- ◯ I don't know
- ◯ Not applicable (I only have experience with one type of wheelchair)

27. If you have experience in using a manual wheelchair, please tell us up to three features of your wheelchair that you consider to be most important. If you prefer not to say, please enter N/a. *

28. If you have experience in using an electric wheelchair, please tell us up to three features of your wheelchair that you consider to be most important. If you prefer not to say, please enter N/a. *

29. Is there anything else you would like to tell us about your wheelchair(s)? If you prefer not to say anything, please enter N/a. *

Your mobility.

30. How many hours per week do you engage in physically intense activities? (e.g. sports, gym etc.) *

- ◯ 0
- ◯ 1-2
- ◯ 3-4
- ◯ 5-6
- ◯ 6-7
- ◯ 7+
- ◯ Prefer not to say

31. In a typical week, how many full days do you spend at home? (i.e. days that you have not left your home at all) *

- ◯ 0 (I go out everyday)
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7 (I never leave my home)
- ◯ Prefer not to say

32. Are you able to stand or move at all without your wheelchair? *

- ◯ Yes
- ◯ No
- ◯ Prefer not to say

33. Is there anything else you would like to tell us about your mobility? If you prefer not to say anything, please enter N/a. *

Your wheelchair tyres.

34. How many times have you inflated your wheelchair tyres in the last 12 months? *

- ◯ 0
- ◯ 1 to 2
- ◯ 3 to 4
- ◯ 5 to 6
- ◯ 7 to 8
- ◯ 9 to 10
- ◯ 11 to 12
- ◯ 13 to 24
- ◯ 25+
- ◯ Not applicable

35. How would you describe your experience with inflating your tyres? *

- ◯ Extremely difficult
- ◯ Difficult
- ◯ Neither easy nor difficult
- ◯ Easy
- ◯ Extremely easy
- ◯ Not applicable

36. How far do you usually travel to access the equipment required to inflate your tyres? *

- ◯ Nowhere (from home)
- ◯ Up to 1 mile (1.6 km)
- ◯ Over 1 mile and up to 2 miles (3.2 km)
- ◯ Over 2 miles and up to 5 miles (8 km)
- ◯ More than 5 miles
- ◯ Changes on a regular basis
- ◯ Not Applicable

37. How many tyre punctures have you had in the last 12 months? *

- ◯ 0
- ◯ 1 to 2
- ◯ 3 to 4
- ◯ 5 to 6
- ◯ 7 to 8
- ◯ 9 to 10
- ◯ 11 to 12
- ◯ 13+
- ◯ Not applicable

38. How would you describe your experience with repairing/replacing your tyres? *

- ◯ Extremely difficult
- ◯ Difficult
- ◯ Neither easy nor difficult
- ◯ Easy
- ◯ Extremely easy
- ◯ Not applicable

39. How far do you usually travel to access the equipment required to repair/replace your tyres? *

- ◯ Nowhere (from home)
- ◯ Up to 1 mile (1.6 km)
- ◯ Over 1 mile and up to 2 miles (3.2 km)
- ◯ Over 2 miles and up to 5 miles (8 km)
- ◯ More than 5 miles
- ◯ Changes on a regular basis
- ◯ Not Applicable

40. Please rank the following characterisitcs that you would want your ideal wheelchair tyres to have. (1st=highest ranked) *

- Puncture Resistant
- High Manoeuvrability
- High Wheeling Efficiency (easy to move the wheels, low exertion)
- Eco-Friendly
- Visually Pleasing
- Shock Absorption / Vibration Reduction (e.g. more comfortable when getting on/off pavements, more comfortable when moving on uneven terrain like gravel)
- High Durabililty (long lasting)
- Low Cost
- Light-Weighted (low in mass)
- Minimal Maintenance Requirements (e.g. tyres don't deflate)

41. From the previous question, which characteristics do your current wheelchair tyres have? *

- [ ] Light-Weighted
- [ ] High Durability
- [ ] Low Cost
- [ ] Eco Friendly
- [ ] High Manoeuvrability
- [ ] Puncture Resitant
- [ ] Low Maintenance
- [ ] Shock Absorption / Vibration Reduction
- [ ] High Wheeling Efficiency
- [ ] None
- [ ] Visually Pleasing

42. What is your preferred tyre pressure? *

- ◯ Higher than recommended (by manufacturer)
- ◯ Recommended (by manufacturer)
- ◯ Lower than recommended (by manufacturer)
- ◯ I don't have a preference
- ◯ Not applicable
- ◯ I don't know the recommended pressure by the manufacturer

43. How would you describe your experience with maintaining your preferred tyre pressure? *

- ◯ Extremely difficult
- ◯ Difficult
- ◯ Neither easy nor difficult
- ◯ Easy
- ◯ Extremely easy
- ◯ Not applicable

44. Have you noticed differences in the performance/handling of your wheelchair when your tyre pressure is not optimal? *

- ◯ Yes
- ◯ No
- ◯ Not sure
- ◯ Not applicable

45. Do you feel that your tyres can provide the highest level of comfort, and the highest level of propulsion efficiency (lowest effort to propel the wheelchair) at the same time? *

- ◯ Yes
- ◯ No
- ◯ I don't know

46. Is there anything else you would like to tell us about your wheelchair tyres? If you prefer not to say anything, please enter N/a. *

General

If you were unsure about any of the questions and require assistance, please contact the researcher at: otis.wyatt@research.staffs.ac.uk

Appendix B – FS-NPT Mass Calculation

Equation for calculating the mass of an FS-NPT in 0. The equation is based off of the 5 design parameters used in the Taguchi analysis.

$$\frac{PT}{\cos(A)} \times \frac{H}{4} = LongPlateArea$$

$$\frac{(2 \times PT \times W) - (PT^2 \times \tan(A))}{2} = ShortPlateArea$$

$$PT \times \left[\sqrt{\left(W \times \left(IS_R + \frac{H}{2}\right)^2\right) \times \left(1 - \cos\left(\frac{360}{S}\right)\right)} - W - 2\left(\tan(A) \times \left(\frac{H}{4} - \frac{PT}{2}\right)\right) - \frac{2 \times PT}{\cos(A)} + \frac{PT \times \tan(A)}{2} \right] = ConnectingPlateArea$$

$$(8 \times LongPlateArea) + (2 \times ShortPlateArea) + ConnectingPlateArea = SingleSpokeArea$$

$$SingleSpokeArea \times S = SpokeArea$$

$$\left(\pi \times {RR_i}^2\right) - \left(\pi \times {OSL_i}^2\right) = OuterSpokeLayerArea$$

$$\left(\pi \times {IS_R}^2\right) - \left(\pi \times {ISL_i}^2\right) = InnerSpokeLayerArea$$

$$InnerSpokeLayerArea + OuterSpokeLayerArea + SpokeArea = TotalSpokeArea$$

$$TotalSpokeArea \times D = TotalSpokeVolume$$

$$TotalSpokeVolume \times S\rho = TotalSpokeMass$$

$$\left(\pi \times {TR_i}^2\right) - \left(\pi \times {RR_i}^2\right) = RingArea$$

$$RingArea \times D = RingVolume$$

$$RingVolume \times R\rho = RingMass$$

$$(\pi \times OR^2) - \left(\pi \times {TR_i}^2\right) = TreadArea$$

$$TreadArea \times D = TreadVolume$$

$$TreadVolume \times T\rho = TreadMass$$

$$TotalSpokeMass + RingMass + TreadMass = NetMass$$

$Where$:

$PT = Plate\ Thickness$

$W = Width$

$A = Angle$

$S = Number\ of\ Spokes$

$RT = Outer\ Ring\ Thickness$

$H = Spoke\ Height$

$IS_R = Spoke\ Inner\ Radius$

$OR = Tyre\ Outer\ Radius$

$TR_i = Tread\ Inner\ Radius$

$RR_i = Ring\ Inner\ Radius$

$OSL_i = Outer\ Spoke\ Layer\ Inner\ Radius$

$ISL_i = Inner\ Spoke\ Layer\ Inner\ Radius$

$D = Tyre\ Depth$

$S\rho = Spoke\ Density\ (TPU)$

$R\rho = Ring\ Density\ (AISI\ 4340)$

$T\rho = Tread\ Density\ (Rubber)$

Mass check using volumes from CAD geometry for optimum tyre model:

$PT = 1.25mm \qquad W = 3mm \qquad A = 25° \qquad S = 106 \qquad RT = 0.25mm$

Spoke volume (CAD):

$$201385.905 \times 10^{-9}\ m^3 \times 1220\ kg/m^3 = 0.2457\ kg$$

Ring volume (CAD):

$$8499.972 \times 10^{-9}\, m^3 \times 7800\, kg/m^3 = 0.0663\, kg$$

Tread volume (CAD):

$$85388.488 \times 10^{-9}\, m^3 \times 1043\, kg/m^3 = 0.0891\, kg$$

Total mass:

$$0.2457\, kg + 0.0663\, kg + 0.0891\, kg = 0.4011\, kg$$

Using equation:

$$0.401038\, kg$$

Percentage error:

$$0.0155\%$$

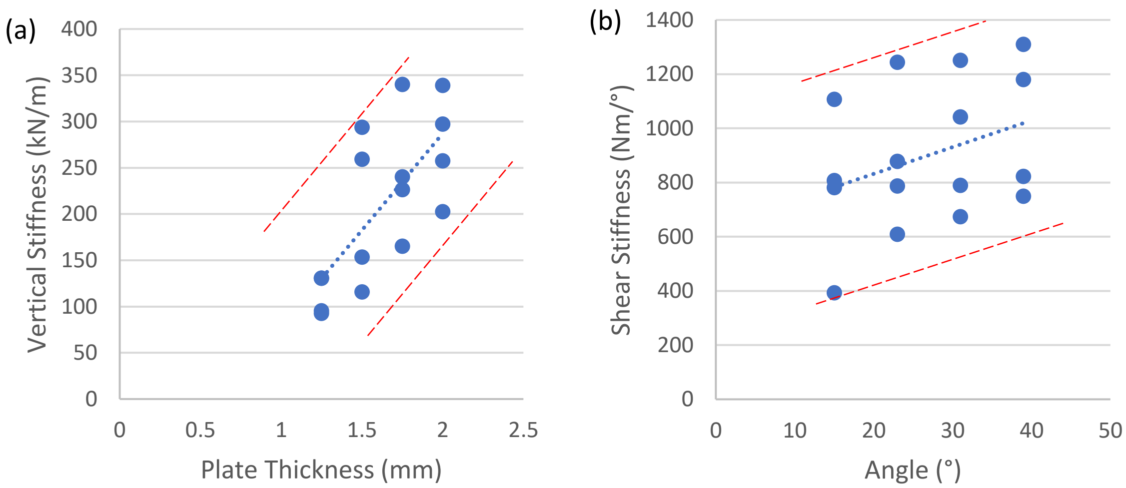
The above highlights the precision of the mass equations in calculating the total mass of the virtual FS-NPTs.

Appendix C – Regression Model Diagnostics

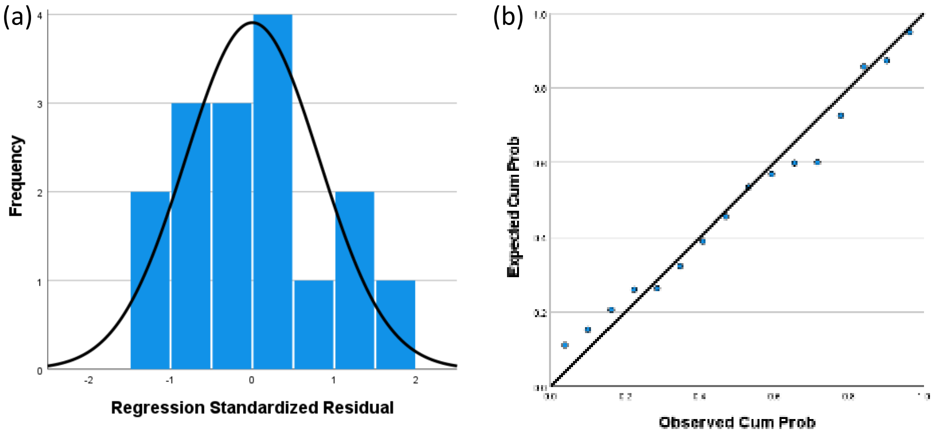
Assessing the multiple linear regression analysis in 0. The results were assessed for multicollinearity, linearity, homoscedasticity, normality of residuals, and outliers.

Table C1 – Correlations for assessment of multicolinearity for Vertical Stiffness. Values of 0 indicate no correlation.

Correlations		Vertical Stiffness L1	Plate Thickness	Width	Angle	Spoke Count	Ring Thickness
Pearson Correlation	Vertical Stiffness L1	1.000	.713	.107	-.505	.279	.314
	Plate Thickness	.713	1.000	.000	.000	.000	.000
	Width	.107	.000	1.000	.000	.000	.000
	Angle	-.505	.000	.000	1.000	.000	.000
	Spoke Count	.279	.000	.000	.000	1.000	.000
	Ring Thickness	.314	.000	.000	.000	.000	1.000



Graph C1 – Assessment of linearity and homoscedasticity. (a) Effect of Plate Thickness on Vertical Stiffness. (b) Effect of Honeycomb Angle on Shear Stiffness.



Graph C2 – Assessment of normality of residuals. (a) Results of tread stresses approximately following a normal distribution curve. (b) Normality probability plot showing close conformity of tread stress results.

Table C1 shows how strongly a parameter correlates with a specific result (vertical stiffness in this example), but also with other parameters (obtained from SPSS output results). Each parameter's correlation with one another all equate to zero, proving multicollinearity is not present in the data for vertical stiffness. This was conducted for all outcome measures.

Examples of two different parameters and outcome measures in Graph C1 shows linear behaviour trends. These tests were carried out for all parameters and outcome measures and were considered valid.

Graph C1 shows dashed lines parallel to the mean trendline at a similar distance apart. The results do not converge or diverge which shows good signs of homoscedasticity. All cases were checked and considered to have consistent error.

The data in Graph C2 tends to conform to a normal distribution curve, and the points on the probability plot conform (to a degree) to the central gradient line, and so this condition is met (checks were made for each outcome measure and considered met).

There were no outliers in this dataset (all result were within 3 standard deviations of the mean).

Appendix D – Peer Reviewed Publications

The findings of the optimal finite element methods in designing a flexible-spoke non-pneumatic tyre for a manual wheelchair in Chapter 6 were published:

Wyatt, O., Chatzistergos, P., Pasiou, E. D., Chockalingam N., Ganniari-Papageorgiou, E. (2023). Exploration of the optimum finite element modelling techniques for honeycomb structures for non-pneumatic tyre applications. Materials Today: Proceedings, Volume 93, Part 4, 2023, Pages 743-747, ISSN 2214-7853. https://doi.org/10.1016/j.matpr.2023.06.040.

The combination of chapters 4, 6, and 8 in the development of a flexible-spoke non-pneumatic tyre were published:

Wyatt, O., Chatzistergos, P., Chockalingam, N., Ganniari-Papageorgiou, E. (2024). A flexible-spoke non-pneumatic tyre for manual wheelchairs. Sci Rep 14, 29032. https://doi.org/10.1038/s41598-024-79689-1