USING ENGINEERING DESIGN TO CREATE BETTER PRODUCTS: AN EXERCISE IN DESIGNING A MOUNTAIN BIKE SUSPENSION SYSTEM

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ABSTRACT

Many consumers have experienced the frustrations of using a product with sub-par performance. With household consumption of products and services contributing to over 60% of greenhouse gas emissions (Ivanova et al., 2015), engineers and designers are obliged to make stronger considerations towards creating effective and robust products.

In many cases these frustrations could be mitigated by applying engineering design techniques throughout the product development process: producing designs with intent to meet product performance criteria and provide users with greater satisfaction.

This research exemplifies the engineering design process of a general-purpose mountain bike suspension system from concept to a manufacturable design. A host of different elements are incorporated, such as the implications of how suspension mechanisms affect the physical forces and perceived feelings on a bicycle, ergonomics, and how these considerations can all be amalgamated into one manufacturable design. Many of the techniques used throughout this design process, and the idea of optimising of the relevant performance criteria, can be applied to a huge array of other projects to minimise the environmental impact of wasteful products in sectors beyond mountain bikes.

INTRODUCTION

This research project was set out as an engineering design exercise to facilitate personal exploration and development. The project comprised of designing a rear wheel suspension system for a bicycle frame (exampled in Figure 1), involving careful integration of various user requirements to optimise performance for a general-purpose mountain bike. This is a pragmatic objective given that designing effective products means they can last longer, reducing product waste and the associated emissions.

Figure 1: A mountain bike with a rear suspension system (highlighted).

Product wastage

Household consumption alone contributes a staggering share of greenhouse gases, estimated at over 60% of global greenhouse gas emissions (Ivanova et al., 2015). Although much of this is associated with consumables, such as water, food and energy supplies, a significant amount will be associated with inconsumable products, such as those designed for consumers' own leisure or convenience.

Most consumers will be familiar with the frustrations of using products where poor design results in sub-par performance. Products which are difficult to use, fail to fulfil their intended purpose, or fail prematurely are likely to be discarded. As effective use of natural resources becomes a focus in mitigating climate change, industries, companies, and designers are obliged to consider the environmental impact of poor product design.

One solution to unnecessary product wastage might be to have all inconsumable products fully recyclable; however, it is important to remember that the recycling processes are often expensive and difficult to do effectively, as well as contributing further emissions by virtue of the energy required to reprocess the materials. It is preferable to use a material to its full potential before reusing or recycling it where possible. Considering this idea and the known impact of product wastage highlights the importance of practising good product design, allowing materials to be used until the end of their maximum lifespan and preventing unnecessary wastage.

The context of mountain bikes

Mountain bikes are a category of bicycles used for off-road cycling which utilise suspension systems, allowing the bicycle's wheels to better follow terrains that may be encountered when riding off road. Having better tyre contact provides more grip, comfort, and control to the rider, as well as reducing the forces and vibrations transferred to their body. The sport has evolved into a spectrum of sub-disciplines, such as cross-country and downhill specific riding, where suspension system characteristics are optimised for a specific type of terrain to better suit the rider's needs and expectations (Partland and Gibson, 2003). Designing a general-purpose mountain bike then implies the need for a versatile suspension system to allow riders to tackle a wide variety of trails.

To illustrate the environmental impact of a typical mountain bike, Trek's Fuel EX model is a general-purpose mountain bike with a rear suspension system where the manufacture of each bike is estimated to produce 153 kg of CO2 emissions (Trek Bicycle, 2021). Based on Equation 1, if this bike is cycled approximately 380 miles, the rider will save the carbon emissions of what it took to make their bike, compared to driving an average car (Trek Bicycle, 2021).

$$\frac{153\,kg\,CO2e}{1\,bike} \times \frac{1\,gallon\,of\,fuel}{8.887\,kg\,CO2e} \times \frac{22\,miles}{1\,gallon\,of\,fuel} = \mathbf{378.8\ miles\ per\ bike} \qquad (1)$$

However, most mountain bikes are used recreationally for exercise and adventuring, rather than for replacing car travel when commuting. The lower potential for a mountain bike to offset carbon emissions increases the importance of designing them for maximum longevity.

All bicycles include some consumable components such as tyres, brake pads, and chains which naturally wear out throughout their use. The major components are not consumables and could generally last the lifetime of the user and beyond if well designed. However, creating an effective design that wholly satisfies the user is a complex task. Historically, ineffective designs often come from poor understanding of the suspension ‘kinematics’. The kinematics of the suspension defines how the system moves due to external forces. Although there could be any combination of forces acting on the bicycle (due to the irregular terrain encountered off-road in combination with the rider moving around to maintain balance and control), there are a few forces which should be especially considered to deliver a good mountain bike. Namely, those from rider inputs of pedalling (acceleration forces) and braking (deceleration forces), as well as bumps in the terrain (impact forces). A bike with poor kinematics will cause the rider to feel uncomfortable, out of control, and unsatisfied with the bike’s performance, risking avoidable replacement or discarding of the product.

How can engineering design help improve products?

The Sharing Experience in Engineering Design (SEED) organisation defines design as ‘the total activity necessary to provide a product or process to meet a market need’ (Childs, 2004). In general, this ‘total activity’ involves processes and tasks to methodically control and understand how a product is realised from a blank canvas to its final state. Design is a creative activity, so the exact processes and tasks used will vary greatly between products, designers, and companies. However, they are commonly categorised into conceptual, preliminary, and detailed design phases. Joseph Harrington, Jr. provides an elegant description of these phases in *Understanding the Manufacturing Process: Key to Successful CAD/CAM Implementation*, as follows:

Conceptual design ‘conducts the necessary research and develops the grand scheme for the product, in response to the assigned product requirements’.

Preliminary design ‘selects an optimised configuration for the product, refines the concept, reconciles the scheme with reality, tests the design with models, and evaluates its ability to meet the assigned specifications’.

Detailed design ‘including layouts and detailed designs for every part, tests the design with prototypes, and prepares the design for transfer to production’ (Harrington, 1984).

Engineering techniques involve transforming maths and physics relationships into useful tools which allow designers to create things with a degree of certainty to ensure that the ‘market need’, or product requirements, are met at the end of the design process endeavours. In this case, one of the most critical product requirements is ensuring that the suspension kinematic forces will complement the rider’s needs and expectations.

DESIGN PROCESS

Design requirements

The first stage of product development is to determine a set of design requirements. Design requirements are a set of fundamental goals that the product must address to fulfil its purpose. Robust design requirements are a prerequisite for a useful product since they essentially guide what the final product will be. A common method of setting out the design requirements is to use a Product Design Specification (PDS) (Childs, 2004). A PDS is a simple document used to organise a range of design requirements into categories and rank them of their importance. The ranking of each statement gives designers a point of reference for prioritising decisions to be made about the design. Initially, the PDS statements should be based on market research into what is expected of the product. However, it is not always clear what a realistically achievable set of design requirements may look like. For this reason, the PDS should be revisited throughout the design process to continually ensure the final design is practically achievable and aligned with what is wanted by the market (Childs, 2004). Table 1 shows the final state of the PDS developed for this general-purpose mountain bike.

Overview of design process

Once the initial design requirements have been laid out, the activity required to meet them as closely as possible can begin. Although a product must evolve from conceptual to preliminary to detailed phases, the path to achieving the final design is not a linear one. Conceptual, preliminary, or detailed tasks may have to be revisited multiple times due to unforeseen consequences of early design assumptions, creating ‘feedback loops’ within the overall process. There is no regimented way to conduct this process either. The nature of human creativity and how designers interpret things in diverse ways depending on personal experience, resources available, psychological factors, etc. will also have a huge influence on the design process itself.

Figure 2 outlines the major tasks used throughout the design process of this project. Conceptual design tasks involved developing the suspension system kinematics to achieve user satisfaction at a fundamental level. Various concepts were explored and the most promising one was selected for further development. Preliminary and detailed design tasks then

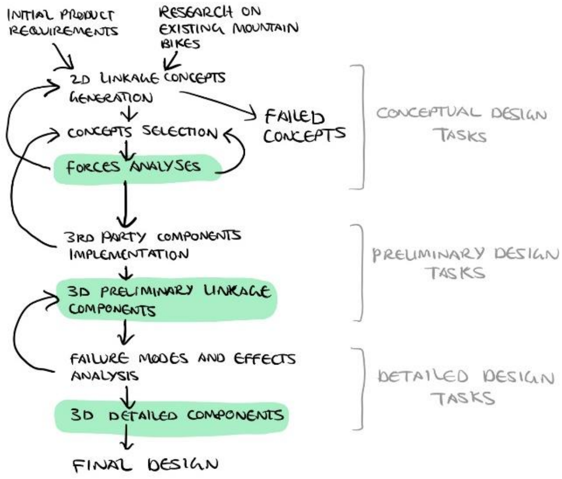


Figure 2: Flow chart outline of mountain bike design process tasks.

Table 1: Final PDS iteration. Statements are ranked 1-5, with 1 being of highest and 5 of lowest importance.

#	STATEMENT	CATEGORY	RANK
1	The system must provide a “progressive” (i.e., rising rate) suspension characteristic with minimal “pedal-bob” and good stability under braking to suit the general-purpose riding application.	PERFORMANCE	1
2	The system must provide at least 130 mm of vertical suspension travel. (Exact amount of travel should be optimised to suit the suspension characteristics).	PERFORMANCE	2
3	The system must be able to be used continuously without any degradation in performance (e.g., due to overheating via the dissipation of kinetic energy).	PERFORMANCE	1
4	The system must operate as intended in ambient temperatures ranging from -10 to 40 °C.	PERFORMANCE	4
5	The system must be sealed to ingress of water, dirt, sand, etc. to IP67 standard.	PERFORMANCE	2
6	The system must allow for at least 1 water bottle (with the largest volume possible, and a minimum acceptable volume of 500 ml) to be fitted to the frame.	USABILITY	2
7	Any adjustable aspects of the suspension should be doable by 1 person, with no tools required.	USABILITY	4
8	The system must allow the user as much space and range of movement as possible. A seat tube length of no more than 400mm should be used and any suspension linkages should not interfere with the rider’s legs.	USABILITY	1
9	The system must not interfere with the following aspects of bike adjustability; adjustable suspension characteristics, adjustable saddle height, can accommodate a range of crank lengths, can accommodate a range of gear ratios.	ERGONOMICS	1
10	The system must be able to accommodate a range of riders in 5th – 95th percentile range of range of height and weight for males and females. This may be broken down into size specific systems for separate, smaller ranges of riders.	ERGONOMICS	3
11	Assembling and maintaining the system should only require 1 person to do so, without custom tools/fixtures (unless supplied).	MAINTENANCE	3
12	Regular maintenance should be required no more frequently than every 12 months or 2000 km of riding.	MAINTENANCE	2
13	Sustainable materials should be used where possible.	MATERIALS	5
14	The system should have a minimum lifespan of 5 years under typical riding conditions.	LIFE SPAN	3
15	The design should avoid infringing on existing patents as far as possible.	PATENTS	5

involved creating the physical implementation of the conceptual design to ensure it could feasibly be built and perform as intended. The methods and results of a selection of techniques used in shaping the final design are discussed in the respective sections, as highlighted in Figure 2.

SELECT TECHNIQUES OF DESIGN PROCESS

Conceptual Design

The rear suspension system of a mountain bike can be viewed as a mechanical linkage. A linkage is an assembly of rotating components (links) which are connected at pivot points. Changing the configuration of the linkage (e.g., by altering link lengths, pivot positions, number of links) will change how it transmits forces. Within contemporary mountain bike designs, rear suspension systems often have 1-6 links, depending on how the designers are trying to control the suspension forces and movement (i.e., the kinematics). Two main techniques were used to control rider input forces (pedalling and braking) and impact forces (from the terrain).

Designing for rider input forces

When a using a bicycle, the rider is repetitively applying varying degrees of acceleration and deceleration forces by pedalling and braking. This acceleration or deceleration is felt by the rider as ‘weight transfer’: the reaction to acceleration and deceleration forces, acting in opposing directions, as illustrated in Figure 3.

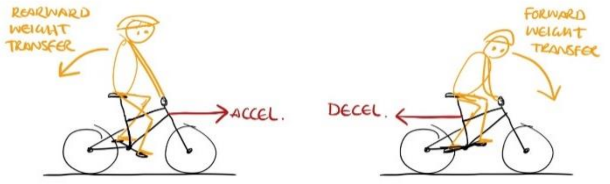


Figure 3: Directions of weight transfer and accelerations.

On a normal bicycle with no suspension, this weight transfer will simply put more load on the front or rear tyre during braking or pedalling, respectively. However, in a suspended vehicle, the suspension linkage is supposed to move freely to absorb bumps. Unfortunately, this freedom of movement also means that the suspension will tend to be compressed or extended by weight transfer effects from the rider, as illustrated in Figure 4.

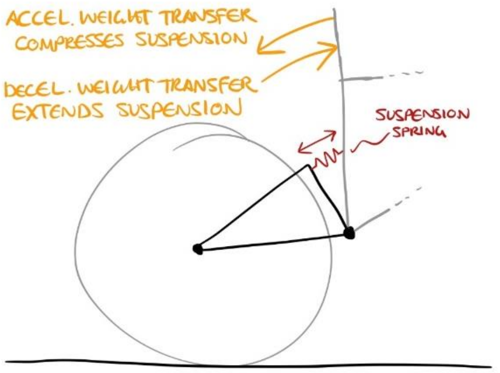


Figure 4: Weight transfer effects on a suspended bicycle.

On a bicycle, the forward/backward pitching of the frame due to suspension extension/compression can be particularly noticeable to the rider and can impact on how enjoyable the bicycle is to use, so it is important to design the linkage to control these effects carefully. Since a rider applies acceleration forces in 'pulses' through each pedal stroke, the suspension will be cyclically compressed by the rearward weight transfer, resulting in a phenomenon known as 'pedal-bob'. As per PDS statement #1, pedal-bob should be minimised as this will deliver a suspension system which feels comfortable to pedal and minimises the amount of rider energy wasted to cyclically compressing the suspension, rather than propelling them forwards. For acceleration, the transmission of forces can be thought of as a 3-step process:

1. Rider applies force to pedals.
2. Chain tension force generated is applied to the linkage.
3. Linkage will want to rotate one way or the other, depending on how it is arranged.

Illustrated in Figure 5 for a simple, single-link suspension system, it is evident that the arrangement of the linkage and the size of the sprockets which the chain rides on will define how the linkage moves when pulled on by the chain force. By analysing the forces involved, engineers can represent the interaction between the chain and linkage geometry by a resultant force 'line of action' (LOA) from the rear wheel contact patch to the point of intersection between the chain and the main suspension link (Foale, 2002). In Figure 5, Arrangement a), the chain force would drive the linkage to try and extend the suspension, and in arrangement b), the chain force would drive the linkage to try and compress the suspension, consolidated by the fact that the force lines of action point in different directions for each arrangement. This characteristic is especially useful to designers since arranging the linkage to cause the extension scenario will help to cancel out suspension compression due to weight transfer when pedalling, and therefore minimise the unwanted 'pedal-bob'. Rearward pitching of suspended vehicles is commonly described as 'squatting', and so, the mitigation of squatting by a suspension linkage is referred to as 'anti-squat' by suspension designers. Arrangement b), as shown in Figure 5, would amplify the effect of squatting under acceleration, termed as 'pro-squat'. This is undesirable for bicycles, showing why linkages must be designed carefully (Foale, 2002).

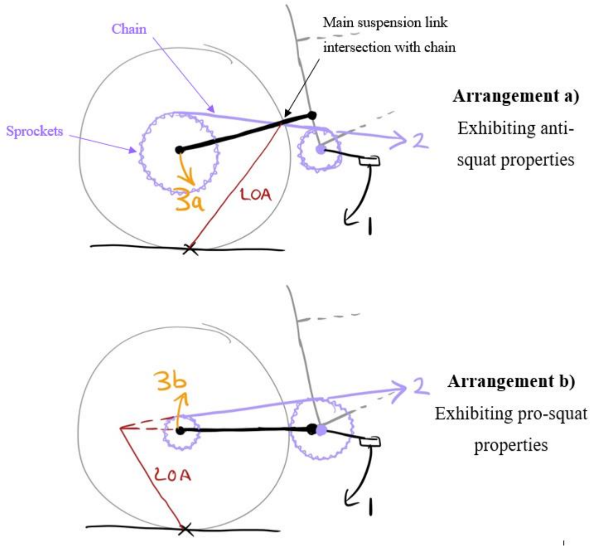


Figure 5: Chain force interaction with suspension linkage.

In terms of braking weight transfer, the suspension system should also be optimised to limit the amount of suspension extension that can occur, as expressed in PDS statement #1. This will minimise how much the bike pitches forwards during heavy braking and prevent the rider from feeling like they will go over the handlebars. For deceleration, the transmission of braking forces can be thought of as another 3-step process:

1. Rider applies the brake, creating a braking torque (a rotational force).
2. Braking torque is transmitted to the bike frame, acting about the main pivot point of the linkage.
3. Linkage will want to rotate one way or the other, depending on how it is arranged.

Again, for a simple, single link system, Figure 6 illustrates how different linkage arrangements will affect the linkage movement under application of braking torque. Unlike anti-squat, there is no interaction with the chain force and the force line of action is defined from the rear wheel contact patch to the main pivot point alone (Foale, 2002). In Figure 6, both Arrangements a) and b) display upwards movement of the linkage due to the braking force, which can help to counteract the forward pitching motion due to extension, or 'rising' of the suspension under deceleration weight transfer. Hence, this property of the suspension linkage is commonly referred to as 'anti-rise'. Arrangements a) and b) will exhibit different amounts of anti-rise, shown by the different gradients of their force lines of action, suggesting how designers can adjust the suspension linkage to choose the degree of anti-rise they want the rider to experience when braking.

To use this method of force analysis as a design tool, the anti-squat and anti-rise properties must be quantifiable. This can be achieved by extrapolating their force lines of action and comparing to the weight transfer force line of action (Foale, 2002). Weight transfer acts about an object's centre of gravity (COG) and is reacted by the front and rear wheels, so the weight transfer force line of action is projected from the rear wheel

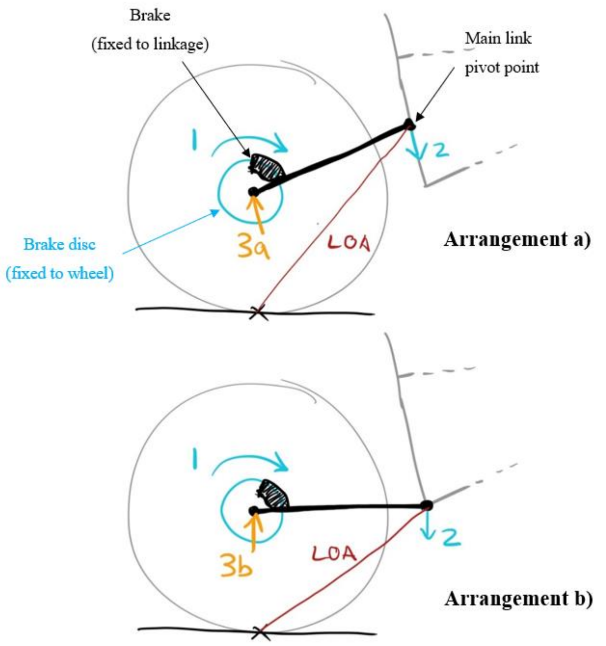


Figure 6: Braking force interaction with suspension linkage.

contact patch to the intersection between the front wheel contact patch and the centre of gravity height. (As an approximation, the COG height is 600-800 mm above the bottom bracket axis for the average rider (Bike Rumour, 2018)). Figure 7 illustrates how the weight transfer, anti-squat, and anti-rise lines of action can be compiled and represented as a percentage where the weight transfer line is considered 100% and the degree of anti-squat/anti-rise relative to this has the following significance:

- *=0%* The linkage will not have any effect on counteracting the weight transfer movement (i.e., the linkage exhibits no anti-squat or anti-rise).
- *<100%* The linkage will resist against, but not overcome the weight transfer movement, so some squatting/rising will still occur.
- *=100%* The linkage will perfectly cancel out the weight transfer movement, so no squatting/rising should occur.
- *>100%* The linkage will act to overcome weight transfer movement (potentially causing rising under acceleration and squatting under braking).

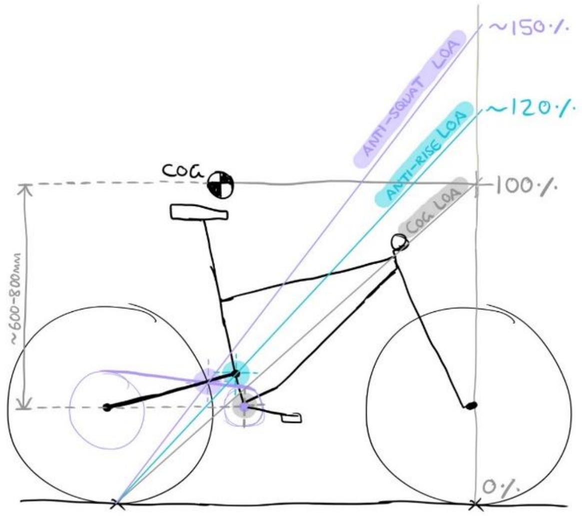


Figure 7: Quantification of force lines of action illustration.

RESULTS AND DISCUSSION

Upon understanding these linkage properties, the task of designing the linkage to deliver the best possible anti-squat and anti-rise values raises a few design problems:

1. As the suspension is compressed, the bike frame will get closer to the ground, lowering the rider atop of it, and consequently, the COG height. This means the lines of action and their associated percentage values will vary throughout the suspension travel.
2. Since both anti-squat and anti-rise properties are dependent on the location of the main pivot point to determine their value, altering the pivot location to improve one property may inadvertently worsen another.
3. There are no explicit ideal values to which every suspension system should aim to achieve throughout its travel, however, the following insights can provide some guidance to designers:
    a. A suspension system should ‘sag’ (i.e., compress) to around one third of its total travel when laden with a rider. This is known as the ‘sag-point’ (Foale, 2002). Therefore, it is expected that this point in the suspension travel will experience most of the rider’s pedalling inputs and it would be wise to aim for anti-squat values around 100% to minimise pedal-bob at the sag-point.
    b. High anti-rise values (>100%) are also typically undesirable since the action of using the linkage to prevent the bike from pitching forward under braking also implies that it is preventing itself from moving freely. In practice, this will make the suspension feel stiffer whilst the rear brake is applied, reducing grip and comfort to the rider.

Since different linkage configurations will vary the anti-squat, anti-rise, and other suspension properties in different ways, it is up to designers to explore this predicament. Linkage X3 is a computer software dedicated to the design of bicycle suspension systems which was used extensively throughout the conceptual design phase. The software helps to solve design problems 1) and 2) by automating the process of calculating suspension system properties using the methods described. This allows the task of linkage design to be approached in a more creative manner through rapid iteration of designs and seeing the effects of changes to the linkage positions throughout the suspension travel, in real time.

Design problem 3) was approached by exploring a wide range of linkage concepts to see how they could control the anti-squat and anti-rise properties throughout the suspension travel. The final design concept was based on a commonly used linkage design in mountain bikes, known as the ‘Horst linkage’, after its inventor, Horst Leitner. Formerly patented (No. US5899480A), its expiration satisfies PDS statement #15, permitting its inclusion in the project. This linkage uses four links, as shown in Figure 8 implemented into Linkage X3. This use of 4 links separates the wheel from being directly connected the bicycle frame, meaning that it does not rotate about a single physical point, like the single-link illustrations in Figures 5, 6, and 7. Instead, the linkage will rotate about a ‘virtual pivot point’ (VPP) which can be found by projecting the geometry of other links in the system and used to construct an equivalent ‘virtual main link’ for computing the anti-squat and anti-rise lines of action (as shown in Figure 8). The virtual pivot point will migrate along a path due to the linkage geometry changing as the suspension is compressed. By altering the linkage to control the virtual pivot point migration path, designers can control how anti-squat and anti-rise characteristics vary throughout the suspension travel.

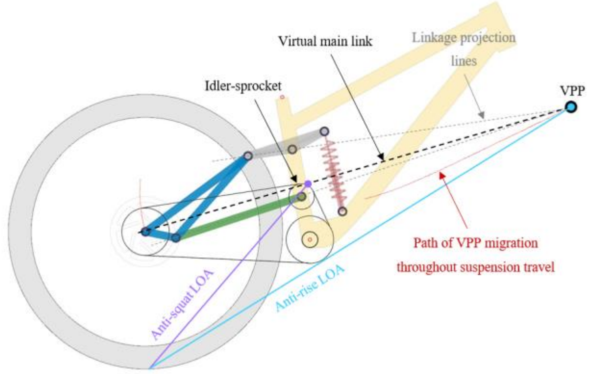


Figure 8: Linkage X3 model of final Horst linkage iteration.

Despite being a relatively old patent, the Horst linkage facilitated the design of a suspension system which exhibits a near constant anti-rise response of ~72% (varying by only ~2% throughout the entire suspension travel), as shown in Figure 9. This should provide stable and predictable braking to the rider in all terrains (i.e., at any point in the suspension travel). To maintain this effective anti-rise characteristic and simultaneously achieve an anti-squat value of ~100% at the sag-point for minimal pedal-bob, an additional idler-sprocket was incorporated. The idler-sprocket (shown in Figure 8) can be positioned independently of the linkage to redirect the chain-line, therefore influencing only the anti-squat values. This provided some freedom to achieve the anti-squat response shown in Figure 10, without affecting the anti-rise response. Ultimately, these characteristics satisfy PDS statement #1, hence the selection of this concept.

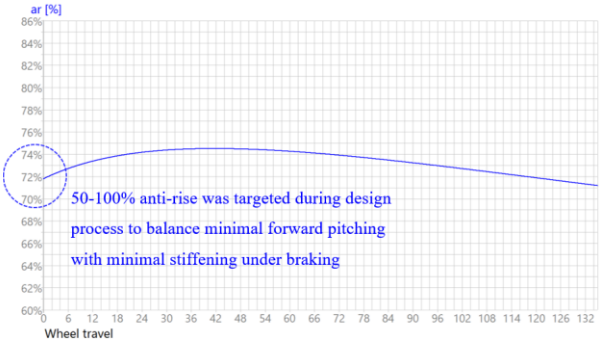


Figure 9: Anti-rise response to suspension travel from Linkage X3.

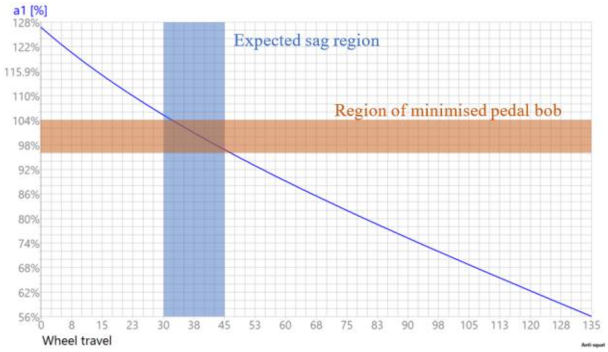


Figure 10: Anti-squat response to suspension travel from Linkage X3.

Designing for impact forces

Methods

The primary function of a suspension system is to absorb impacts and the way that the suspension system handles these impact forces will greatly influence how the bike feels to the rider. Using the relationship for a typical spring (see Equation 2 and Figure 11), the compression force required to displace a spring by a given amount can be found.

$$F_{spring} = k \times z_{spring} \tag{2}$$

where F_{spring} = force required to displace the spring by z_{spring};
k = spring rate constant;
z_{spring} = spring displacement.

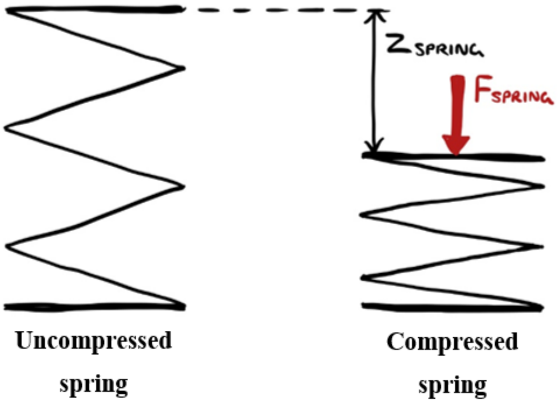


Figure 11: Representation of spring force relationship symbols.

When designing a suspension system's response to impacts, the impact force required to displace the rear wheel (rather than the spring) can also be calculated by incorporating a value to describe the mechanical advantage of the rear wheel over said spring. One way to describe a system's mechanical advantage is using the 'leverage ratio', which is defined as the ratio of wheel displacement to spring displacement (e.g., for every 1 mm the spring is compressed, the wheel will have travelled through 3mm if the system has a leverage ratio of 3:1). Analogous to an asymmetrical 'seesaw', Figure 12 illustrates how the leverage ratio is inversely proportional to the force transmitted by the linkage. Based on this relationship, Equation 2 can be modified to achieve Equation 3 for finding the impact force required to generate a given amount of spring displacement.

$$F_{wheel} = \frac{1}{L} \times \left(k \times z_{spring}\right) \tag{3}$$

where F_{wheel} = force required to displace the wheel;
L = leverage ratio (i.e., z_{wheel}/z_{spring}).

For single link systems like the seesaw analogy, the wheel and spring will always move proportionally to each other (as illustrated by Figure 13, arrangement a)). Therefore, when analysed throughout the suspension travel, the leverage ratio will have a constant value and the compression force will increase linearly by virtue of Equations 2 and 3. Hence, this system is said to have a linear characteristic in response to impact forces.

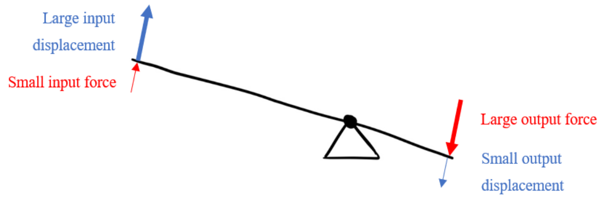


Figure 12: Representation of relationship between displacement and force transmitted by a linkage.

However, a general-purpose mountain bike is inherently exposed to a wide range of impact forces from small bumps like tree roots, to descending large drops which impart a much greater force. A linear increase of impact force capacity may not be enough to withstand larger impacts without using all the available suspension travel and abruptly transmitting those forces to the rider's body. A 'progressive' system may then be desired (as noted in PDS statement #1) to progressively ramp up how much force is required to compress the spring, giving a more supportive feel and a larger capacity for absorbing impacts without jarring the rider.

A progressive system can be achieved by using a multi-link linkage to remove the direct connection between the wheel and spring, thereby allowing them to move at different rates (as illustrated by Figure 13, arrangement b)). The fact that each end of the linkage no longer moves proportionally to one another implies that the leverage ratio, and impact force capacity, will also vary throughout the suspension travel. For example, at the start of the suspension travel, the system may have a leverage ratio of 3:1, and by the end of the travel, the intermediate links have increased the rate of spring compression to display a leverage ratio of 2:1. This decrease in leverage ratio, causes an increase in impact force capacity due to the inverse relationship covered in Equation 3.

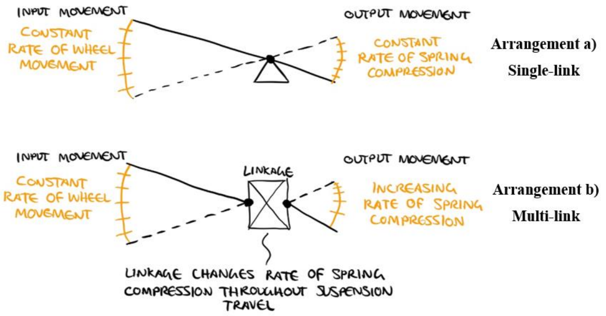


Figure 13: Effects of linkage arrangements on rate of wheel/spring movement.

Like anti-squat and anti-rise properties, Linkage X3 has functionality to automatically solve the system leverage ratio and associated impact forces incrementally throughout the suspension travel, generating a leverage curve and an impact force curve (shown in Figures 16 and 17). This allows designers to focus on manipulating the linkage arrangements and pivot point positions to achieve the desired leverage and force curve characteristics.

A multi-link system had already been employed in designing the bike's responses to rider input forces, however it was found that this linkage could not be made progressive enough without altering the current pivot point locations, and therefore the anti-squat and anti-rise characteristics too. Various concepts were then explored, incorporating a secondary 'spring linkage' to compress the spring without disturbing the existing 'wheel linkage'. The final design is shown in Figure 15 (an illustration of how the overall system moves can be found in Appendix A). This design was primarily selected based on its ability to provide 29% of progressivity in leverage ratio (ranging from 2.8:1 to 2.0:1 throughout the suspension travel), and subsequently, a 22% higher maximum impact force than the baseline single-link model. This design was also most promising in terms of other design requirements, such compactness (to allow space in the frame for water bottle(s), implied by PDS statement #6). Around 30% of progressivity was targeted, based on research into current mountain bike designs aimed at rugged terrain riding. This provides a good amount of suspension support, without feeling too aggressive in the force ramp-up. The leverage and force curves to achieve these results are shown in Figures 16, and 17, with comparisons to an otherwise equivalent, single-link system (shown in Figure 14).

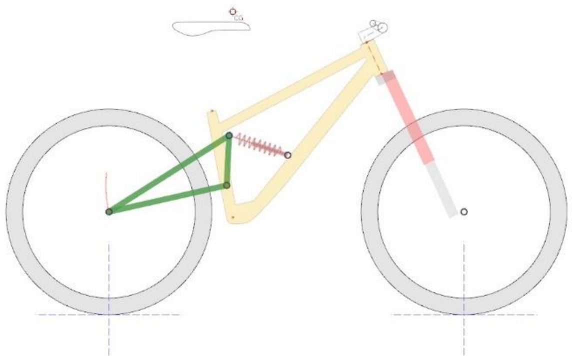


Figure 14: Linkage X3 model of single-link system.

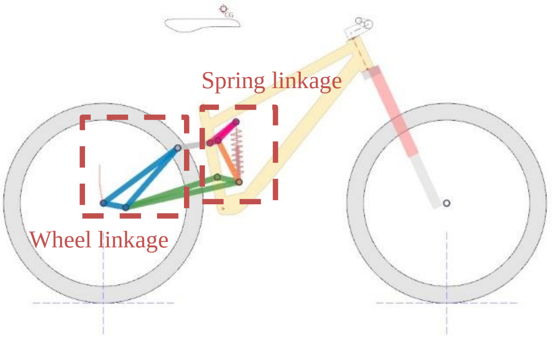


Figure 15: Linkage X3 model of final multi-link system.

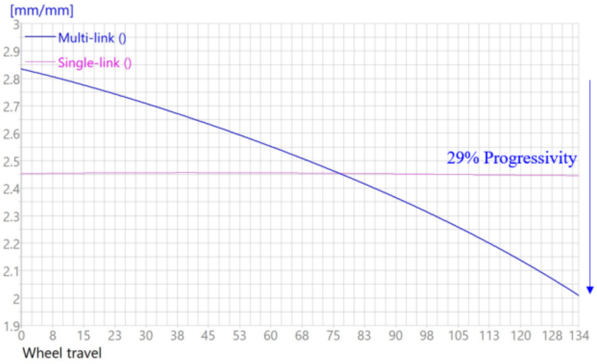


Figure 16: Leverage curves comparison from Linkage X3.

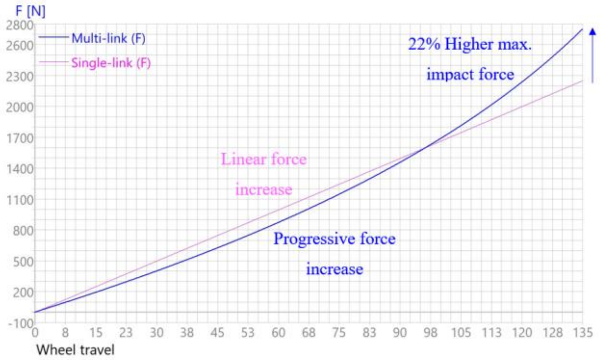


Figure 17: Force curves comparison from Linkage X3 (exampled for a typical 100 N/mm spring).

Preliminary design

A 2D linkage design with promising kinematics is a foundation for satisfying users, however, one of the most challenging aspects of designing a suspension mountain bike frame is the 3D ‘packaging’. This is due to spatial constraints from third-party bicycle components (e.g., wheels and tyres), complex linkage arrangements, and other design requirements competing to fit within a relatively small space between the rider’s legs. The preliminary design phase is essentially a rough assessment of whether the conceptual design can be packaged successfully without causing severe interference/overlapping issues between components or the rider, at any point in the suspension travel.

Methods

By bringing the 2D linkage geometry from Linkage X3 into a 3D CAD program, other dimensions can be incorporated to verify the spatial feasibility of the concept. Anthropometric data on human leg dimensions were obtained from The Measure of Man and Woman: Human Factors in Design to create an accurate model of a leg for a 50th percentile in height male (Henry Dreyfuss Associates, 1993). Models of the relevant third-party components were also created using dimensions from their respective manufacturers, allowing the packaging model shown in Figure 18 to be produced. Preliminary dimensions for thicknesses, etc. of linkage components were estimated by looking at existing mountain bike designs.

Results and Discussion

The results of this preliminary modelling process showed that the linkage was feasible to exist in 3D without significant problems. Figures 19 and 20 show the notable examples of interference issues encountered. Interference issue 1) shows overlapping between the ankle area and a linkage component, however this can easily be rectified by adjustment of the lower link profile during detailed design phases. Interference issues 2) and 3) show potential for overlapping components but depend on the exact size of components used to create the physical pivot points (i.e., bearings, etc.). It is expected that these issues are not severe enough for the design to be abandoned, so it will be passed onto more detailed phases to ensure that compact enough arrangements of pivot bearings can be used.

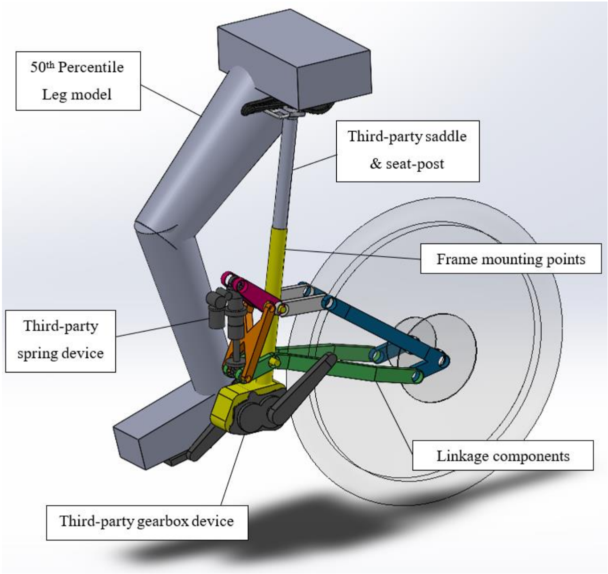
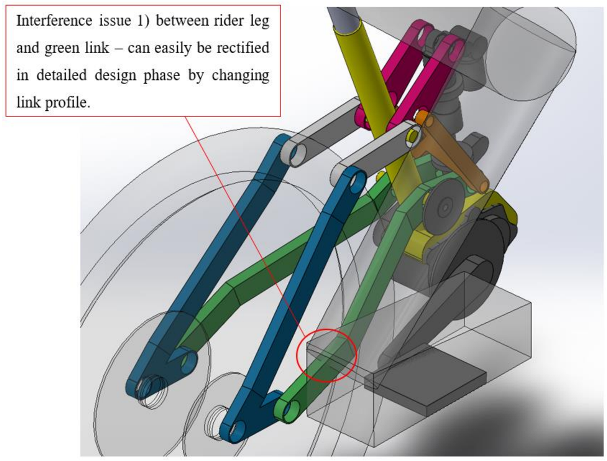
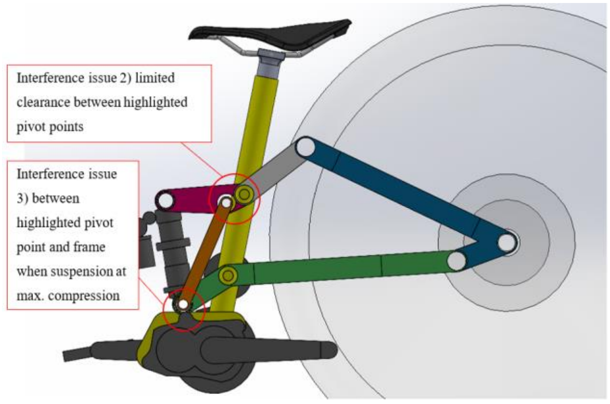


Figure 18: Preliminary packaging model, produced in SolidWorks.



Interference issue 1) between rider leg and green link – can easily be rectified in detailed design phase by changing link profile.

Figure 19: Interference issues with leg model.



Interference issue 2) limited clearance between highlighted pivot points

Interference issue 3) between highlighted pivot point and frame when suspension at max. compression

Figure 20: Interference issues within suspension system.

Detailed design

Based on the outcomes of the preliminary design phase, it now makes sense to start adding more detail to the design. To mitigate the interference issues raised by the preliminary design, selection and arranging of ‘machine elements’ (such as bearings, seals, and fasteners) was undertaken. Thoughtful design of machine element arrangements also simultaneously ensures the best performance of the physical product to achieve its expected performance (e.g., by designing to achieve minimal friction and ensure smooth operation of the system).

Methods

The size of machine elements is generally proportional to their 'load capacity' (i.e., how much force they can withstand before failure), so an analysis of one of the worst-case loading scenarios for the system was conducted to check if small enough components could be used to solve the interference issues highlighted by the preliminary design model. This involved typical methods for static analysis of rigid linkages since a linkage becomes effectively static at the end of its travel (Meriam and Kraige, 2012). This allows the highest expected forces at each pivot point to be calculated (compiled in Figure 21) as a result of the maximum impact force when using the stiffest spring available from the chosen manufacturer (with a spring constant of 140 N/mm).

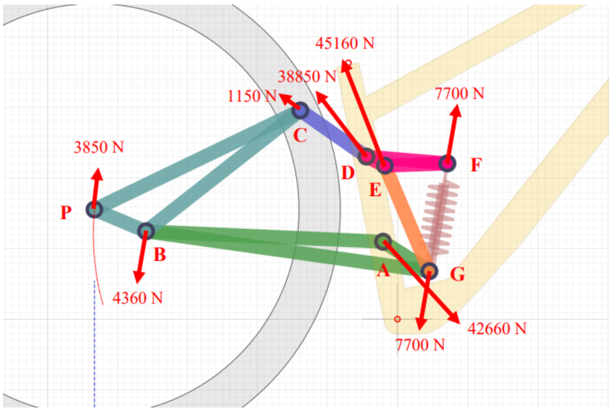


Figure 21: Bearing loads illustration (directions are approximated for illustrative purposes only).

For quick visualisation and to save time wasted on creating 3D models of ineffective arrangements, arrangement sketches can convey the minimum amount of information required to verify the functionality of a design. As exampled in Figure 22, these sketches are based on principles commonly used in the context of mechanical design, such as those described in *Product Design for Manufacture and Assembly*, to minimise part counts and include component features to make manufacturing/ assembly processes easier where possible (Boothroyd, Dewhurst, and Knight, 2011).

Dimensions and maximum load ratings can then be sourced from bearing manufacturers (e.g., SKF) to create a dimensionally accurate 3D packaging model which also satisfies the load bearing requirements shown in Figure 21 (including factors of safety) and re-check the areas where interference issues are expected.

Results and Discussion

Based on the load requirements found and the resultant updates to the packaging model using dimensionally accurate machine elements, interference issues 2) and 3) can be mitigated. These results are shown in Figures 23 and 24.

CONCLUSIONS

Final mountain bike design

Although not a complete representation of the entire design process undertaken, the techniques shown introduce the co-dependent nature of suspension properties due to their shared linkage geometry, and therefore the overarching theme of compromise associated with designing mountain bike suspension systems. Despite the compromises made, the final design is expected to fulfil its general-purpose intentions resulting from understanding the different forces associated with riding a mountain bike and using appropriate engineering design techniques.

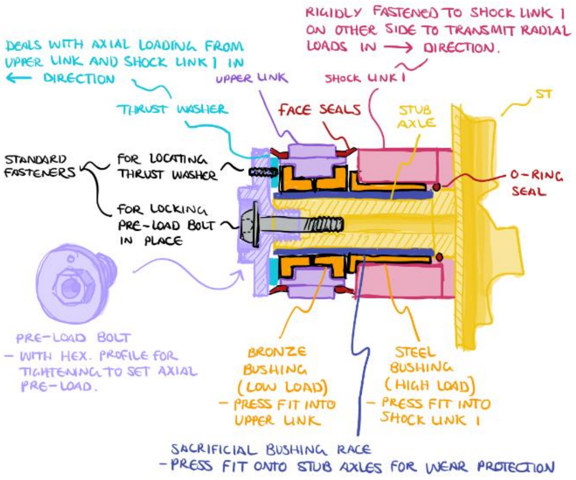
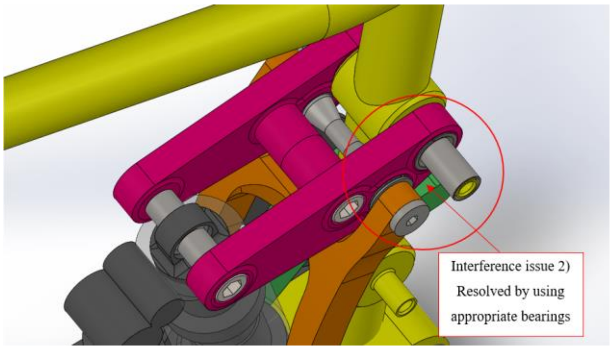
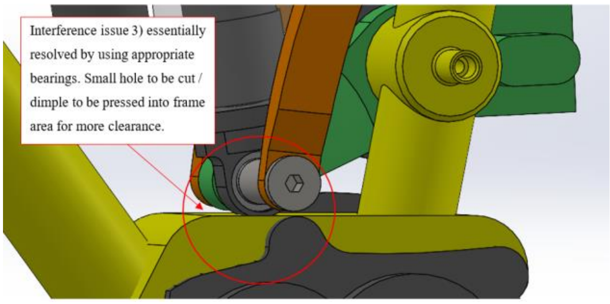


Figure 22: Example arrangement sketch from design process, showing a cross-section of one of the pivot points noted for interference issue 2.



Interference issue 2) Resolved by using appropriate bearings

Figure 23: Interference issue 2, final state.



Interference issue 3) essentially resolved by using appropriate bearings. Small hole to be cut / dimple to be pressed into frame area for more clearance.

Figure 24: Interference issue 3, final state.

This is reflected by the computer model results and meeting of the following PDS statements which were relevant to the techniques discussed:

- Statement #1) SUCCESSFULLY MET. The system displays 29% progressivity, with ~100% anti-squat characteristic occurring at the expected sag region to minimise pedal-bob, and ~72% anti-rise characteristic to reduce forward pitching under braking and varying only ~2% throughout the suspension travel for a stable and predictable braking feel.
- Statement #2) SUCCESSFULLY MET. The system provides ~135 mm of suspension travel whilst meeting the suspension characteristics noted in Statement #1).

- Statement #6) SUCCESSFULLY MET. The system uses compact linkage arrangements, leaving ample room for an estimated 1-3 water bottles within the frame triangle.
- Statement #15) SUCCESSFULLY MET. The system does not include elements which infringe on any existing patents as far as the author is aware.

Despite not meeting all PDS statements in the time frame available, it was useful to include them to guide other design decisions as they were made and simulate the design of a product being brought to market. Based on the preliminary and detailed design phases, the design can currently be considered physically implementable and could now be progressed further for real world testing of prototypes to ensure that all PDS criteria are met, and components are refined for efficient production methods.

General conclusions

Using a controlled process and engineering design techniques has delivered a product which is expected to satisfy users and be considered 'worthwhile' in terms of its material value. As well as serving as a design exercise, this project shows how careful product design can influence a reduction in product wastage and the associated greenhouse gas emissions. Though designing good products is not the sole solution to the problem of produce wastage, the accompanying research to this project points to more sustainable models being adopted in the bicycle industry, with offerings from the likes of Santa Cruz Bicycles including lifetime warranties on their bicycle frames since 2015 (Santa Cruz Bicycles, 2015), and the existence of a companywide sustainability report from Trek Bicycles (Trek Bicycle, 2021).

Many of the techniques shown can be applied to designing other types of mountain bike (e.g., for cross-country, or downhill riding) as well as to other suspended vehicles, or linkage-based systems (such as aircraft landing gear, cranes, tools, etc.). The general idea of using a rigorous process to extract the truly desirable product can be applied to the design of any product, for the benefit of creating something which satisfies its users for as long as possible.

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APPENDIX

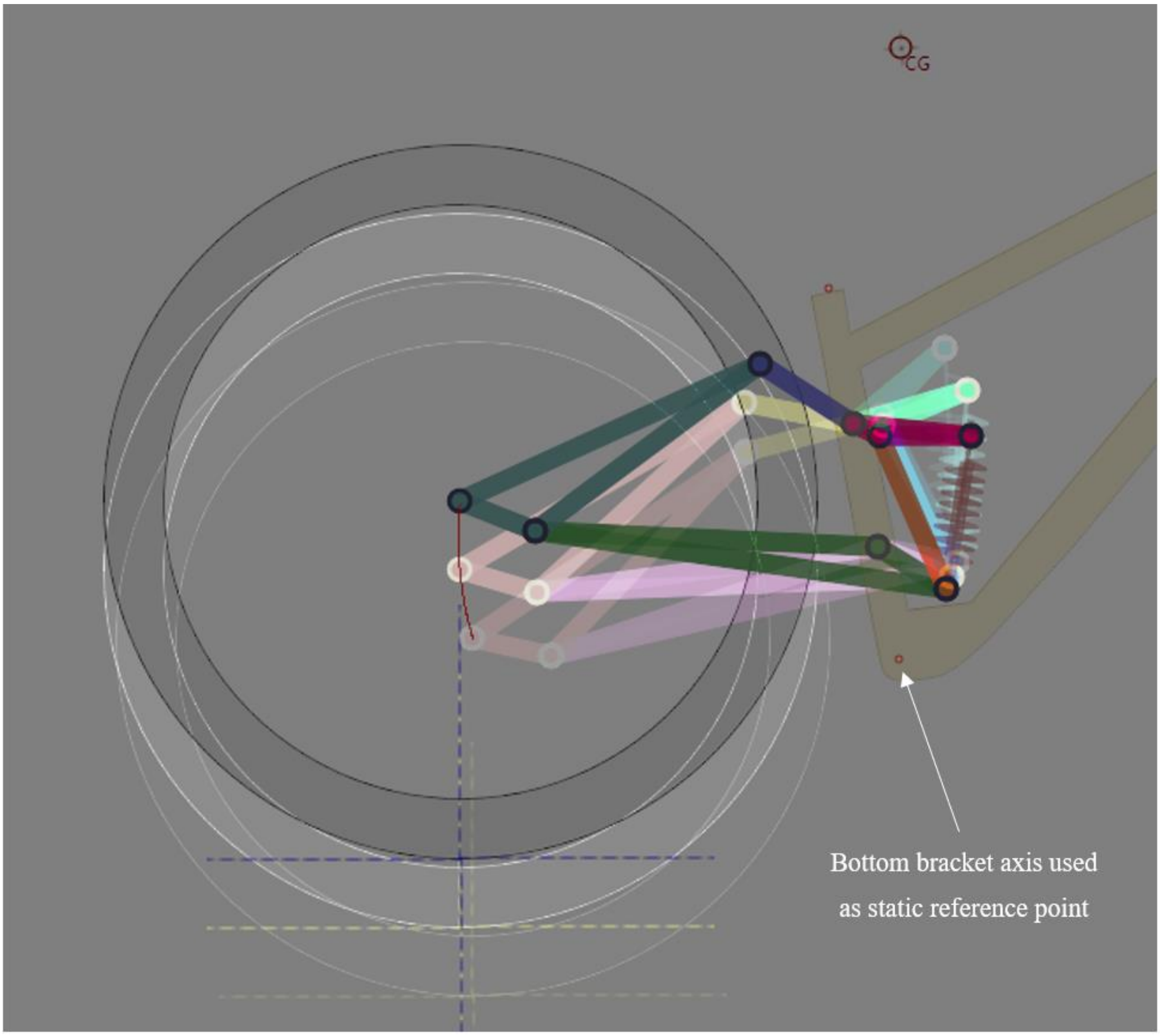

Figure A 1: System movement illustration. Colours altered for clarity.