The Biomechanics of Bruising

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date:

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Abstract

When an individual claims to have been subject to a physical assault, observation of physical injuries such as abrasions, avulsions and bruising can prove to be vital pieces of evidence. Bruising is the most common of these injuries, yet there is a lack of understanding of the parameters required for their formation. Furthermore there is little agreement on a standard method of documentation which allows for an accurate time of injury to be determined.

Little research has been done into the mechanical parameters required to initiate bruising, thus this study investigates if such parameters can be determined and how they influence the colour development of the resulting injury.

Colour studies have been performed with an aim to determine if there is a consistent colour pattern between individuals, without much success. Imaging studies have investigated if an optimal method of documentation could be employed, providing clear contrast between bruise and skin. Furthermore, they have aimed to establish if bruises can be detected while no longer visible to the naked eye. The latter category has shown more promise even though positive findings have been limited. This study investigates the specific RGB values produced in bruise development and healing after a controlled impact is applied. Furthermore, IR and UV imaging techniques are assessed on their ability to detect bruising when no longer visible to the human eye.

This study found that for each applied impact a consistent profile was produced for all participants. The level of specific characteristics observed such as maximum force and peak stress varied inter-person as a result of inaccurate methodology and varying anatomy between participants. RGB value tracking showed a general trend between all participants however, the levels of each colour did not appear to be affected by the different mechanical parameters applied. Colour imaging was successful in the recording of bruising, with ultraviolet imaging also proving successful. Infrared imaging proved problematic with no positive results being observed. This study was also unsuccessful in the identification of bruising after the injury was no longer visible. It is concluded that this field of investigation requires further, more in depth, investigation before a complete understanding of bruising can be achieved.

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1 Introduction

1.1 The Problem of Bruise Interpretation

Identifying and determining the age of a bruise during forensic investigations is a useful means of supporting or refuting a claim of abuse which has resulted in physical injury. The ability to do so becomes more important in cases which involve children or elderly victims, who may be unable to communicate the time at which they received their injuries or how they received them.

The current standard method of visual assessment of a bruise is considered extremely unreliable as it is highly subjective: the method is entirely opinion-based, with varying expert views on which bruising characteristics are of most relevance to its age (e.g. colour variation and intensity, size or if swelling is present).

Cases which have involved a misinterpretation of bruise evidence include that of a Mr. Mullins-Johnson in Canada. In this case, the accused had been charged with first-degree murder of his niece, whom he had been babysitting. The bruises found on the child's body indicated that the child had been sexually assaulted and murdered however, the case was reopened when the 'expert's' opinions were called into question. The injuries were shown to 6 pathology experts who all stated that the bruising evidence would have resulted from the biological changes which occur after death. Thus, the original expert's opinion was found to be flawed (Cromwell 2011).

Furthermore, there are many person-specific factors which affect an individual's tendency to bruise, the extent of the developed bruise and the time taken for a bruise to heal. Such influencing factors include a person's age, gender and medical history. Furthermore, if no medical history is known, bruising which has resulted from a physical injury can be confused with symptoms of a bleeding disorder. This difficulty is acknowledged by medical experts, including Dr. Michael Laposata (pathologist specializing in bleeding and clotting disorders). He states that if he was to be shown images of individuals with bruising, he would not be able to distinguish between which one resulted from a physical assault and which is from a bleeding disorder (Frontline 2011).

As a result, bruises cannot be defined with absolute certainty. This makes their use as definitive evidence of the size of force which produced an injury and the time of injury somewhat inaccurate. Therefore, it should come as no surprise that in some circumstances expert witness testimonies may contradict one another.

1.2 Investigation Aims

The objective of this study is to assess the mechanical parameters surrounding the formation of a bruise and to determine if there was any correlation between the ratios of colours present (rather than range or intensity), with the bruise age and the mechanical parameters of the cause.

The timeline stages of bruise formation and healing will also be explored through analysis of the effects of a known force profile upon a limb. Furthermore, infrared and ultraviolet imaging will be used in an attempt to visualise any non-visible bruise characteristics and to determine if a bruise can be detected after appearing fully healed to the naked eye.

This study aims to bring together the findings of previous investigations in an attempt to evaluate and understand bruise initiation, development and healing. By using a more realistic replication of impact, this study could ultimately lead to a more accurate and standardised method of bruise analysis.

2 Bruising

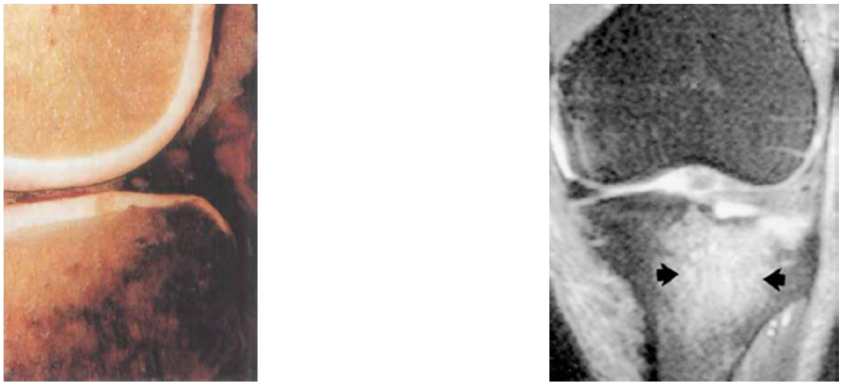
2.1 Defining a Bruise

A bruise is generally defined as the collection of blood in a localized area, resulting from a blunt force impact which has ruptured small veins and capillaries. There are various terms which can be used to describe this type of injury, including contusion, ecchymosis, haematoma and subcutaneous bleeding. Contusion and ecchymosis have the same definition as a bruise and are almost always caused by a blunt force trauma. Subcutaneous bleeding also has the same definition as a bruise however, it specifically relates to bleeding within the subcutaneous layer of the skin and not within the dermis or deeper tissues such as muscles or internal organs. In comparison, haematoma refers to the formation of a blood clot and will generally result from greater impact forces. Commonly, these terms (excluding haematoma), are used to describe dermal bruising however, bruising can also be defined as skeletal (periosteal) or muscular (intramuscular). (Stephenson 1995; Dimitrova et al. 2006; Vij 2011; Huang et al. 2012; Bilo et al. 2013).

2.2 Skeletal and Muscular Bruising

Both skeletal and muscular bruising are deep bruises which result from extreme levels of force or pressure, typically due to the body impacting with a blunt, wide object. Unlike the skin which is characteristically deformable and elastic, muscles and in particular bone, have a greater resistance to movement and immediate recovery. Thus, they are more likely to sustain injury when subject to high impacts (Gunn 2009; Byard 2012).

Skeletal bruising (Figure 2.1), will result from a direct impact to the bone. This can either result from adjacent bones coming into forceful contact with one another (e.g. the femur and the tibia), or a blunt force impact (Sanders et al. 2000).



a. **b.**

Figure 2.1: *Skeletal Bruising of the Tibia – a. Colour Image, Bruise Indicated by Area of Dark Discolouration b. MR Image, Bruise Indicated by Arrows* (Rangger et al. 1998; Sanders et al. 2000)

Muscular bruising (Figure 2.2), results from a blunt force impact which compresses the muscle against the underlying bone. This results in a haematoma formation. As well as serious physical assaults, this type of bruising is commonly observed within sporting injuries (Diaz et al. 2003).

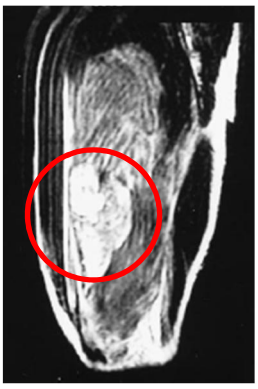


Figure 2.2: *MR Image of Bruising of the Quadriceps – Bruise Indicated By Red Circle* (Adapted from Diaz et al 2003)

2.3 Dermal Bruising

Dermal bruises are the most common type of bruise and are located in the underlying layers of the skin and not on the surface. The skin is the largest organ and outermost protective layer of the body, therefore it is the contact surface of most impacts. As a result it is the body's most damaged organ and any bruising can represent both minor and more serious internal damage (Bilo 2013).

2.3.1 Anatomy of the Skin

The skin, also called the cutaneous layer, covers the majority of the body. Its key functions include providing protection to the internal tissues and organs from abrasions, shocks, foreign chemicals and microorganisms. This layer also participates in regulation processes such as temperature control, nutrient storage and the excretion of molecules such as water and salts. Skin can be divided into 3 main layers, the epidermis, the dermis and a supporting subcutaneous layer (Martini 2004).

2.3.1.1 Epidermis

The epidermis is the outer layer of skin which acts as the 'protective layer'. It is avascular, thus receives oxygen and nutrients via diffusion from the capillaries found within the dermis. However, the outermost layers of the epidermis are dead cells due to being too far from the dermis to survive (Martini 2004; Vij 2011).

The structure of the epidermis consists of either 4 or 5 layers. 'Thin' skin is found to cover the majority of the body and has 4 layers. 'Thick' skin has 5 layers and is found in the soles of the feet and the palm of the hands (Vij 2011; Martini 2004).

The 5 layers of the epidermis are the *stratum corneum*, *stratum lucidum*, *stratum granulosum*, *stratum spinosum* and the *stratum basale*. The *stratum basale*, or *stratum germinativum* as it is also known, is the innermost layer. It comes into contact with the basal lamina which separates the epidermis from the dermis and is the site of cell mitosis. The next layer is the *stratum spinosum* which consists of 8 to 10 layers of living cells. Next, the *stratum granulosum* is the layer where cells stop dividing, begin to produce keratin which reduces cell membrane permeability, dehydrate and ultimately die. Above this layer is the *stratum lucidum*, which is only found in 'thick skin'. It consists of densely packed cells containing keratin. Finally, the *stratum corneum* is the outermost layer consisting of 15-30 layers of keratinized cells which provide the protection from microorganisms and other foreign chemicals. These layers are indicated in Figure 2.3 (Martini 2004; Vij 2011).

2.3.1.2 Dermis

The dermis, also shown in Figure 2.3, is located between the epidermis and the subcutaneous layer. It contains blood and lymph vessels and nerve fibres and can be subdivided into 2 layers, the first of which is the *stratum papillarosum* or papillary layer. This layer is composed of loose thin collagen fibrils bundled within thicker collagen fibres, containing the capillaries which supply the epidermis. Below this is the *stratum reticularosum* or reticular layer. This layer is composed of dense, irregular, thicker collagen fibrils and is in contact with the subcutaneous layer (Silver, Freeman and DeVore 2001; Martini 2004; Vij 2011)

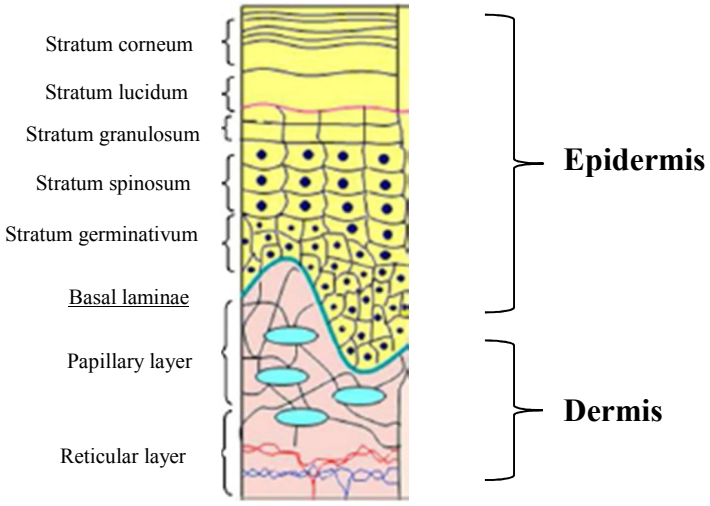


Figure 2.3: *Layers of the Epidermis and Dermis* (Adapted from Ciarletta and Amar 2012)

2.3.1.3 Subcutaneous Layer

The subcutaneous or hypodermal layer is located beneath the dermis and is composed of areolar and adipose tissues and has an elastic structure. Its function includes the stabilisation of skin position in relation to underlying internal organs or skeletal muscles whilst allowing skin movement. It contains larger arteries, a large venous circulation and it is largely responsible for energy storage and shock absorption (Martini 2004).

The thickness and distribution of this layer varies between individuals based on their gender and age. Infants and young children tend to have a thicker, more even distribution and is commonly known as ‘baby fat’. This is because it serves to reduce heat loss and act as a shock absorber as the child becomes increasingly mobile,

inevitably falling over whilst learning to walk. As the child becomes older, the distribution of this adipose tissue alters. Within men it becomes more prominent within the lower back, neck and arms, while in females it is most prominent in the breasts, thighs and hips (Martini 2004).

2.3.2 Definition of Dermal Bruising

Dermal bruising refers to the rupture of blood vessels, generally within the subcutaneous layer of the skin. Once ruptured, red blood cells enter into the dermis and/or adipose tissues (Figure 2.4), where it accumulates and is subsequently broken down and eliminated from the body. The accumulation and degradation of blood is what produces the characteristic skin discolouration associated with dermal bruising (Martini 2004; Dimitrova 2006; Vij 2011).

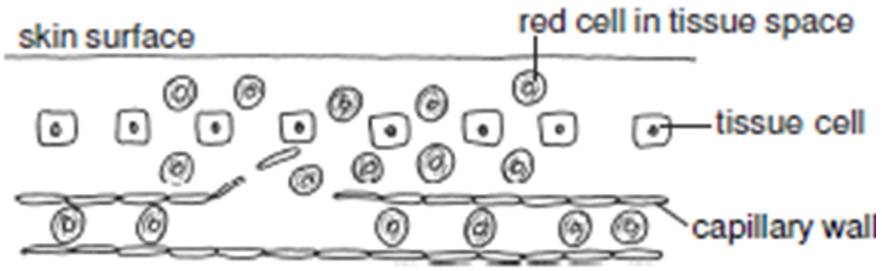


Figure 2.4: *Release of Red Blood Cells into Surrounding Tissues* (Wounds and Healing 2013)

This form of bruising is the most common injury observed on individuals and can be a result of daily activities such as sports or can be an indicator of much more serious incidents of assault or abuse (Bilo 2013).

2.4 The Healing of a Dermal Bruise

2.4.1 Repair of Blood Vessels

Once a blood vessel ruptures, the body reacts by instigating the process of haemostasis. This process aims to stop the bleeding into the surrounding dermal and/or subcutaneous tissue, prevent any further blood loss via the damaged vessel walls and build the framework required for tissue repair (Martini 2004).

Haemostasis (Figure 2.5) occurs as a result of 3 phases known as the vascular, platelet and coagulation phases. During the vascular phase, the local, damaged vessel walls contract to reduce blood loss. The endothelial cells of the vessel then contract exposing the basal lamina to the blood stream. The endothelial cells also release hormones and chemical factors, which stimulate further division of endothelial cells, smooth muscle cells and fibroblasts required for vascular repair. The cell membranes become sticky, ready for attachment of platelets (Martini 2004; Wounds and Healing 2013).

During the platelet phase, circulating platelets migrate towards the damaged vessel and join with the sticky endothelial cells, basal lamina and the collagen fibres within the exposed vessel wall. This step is known as platelet adhesion. As the number of platelet cells attaching increases, platelet aggregation occurs as the platelets join with each other. This ultimately leads to the formation of a platelet plug from which a blood clot can form (Martini 2004).

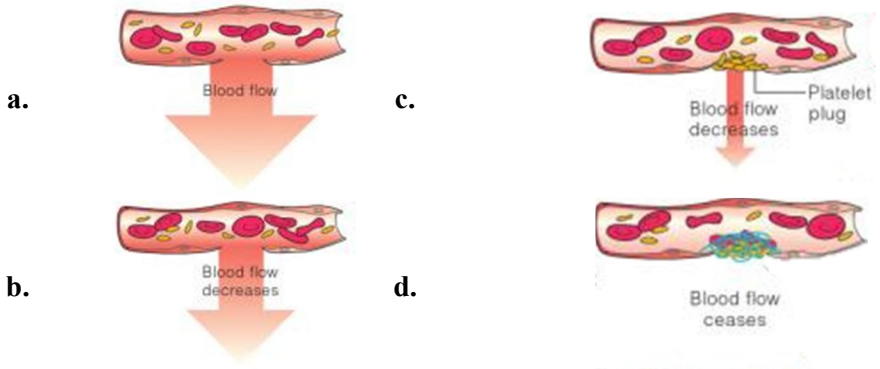


Figure 2.5: *Haemostasis – a. Ruptured Blood Vessel b. Vasoconstriction c. Platelet Adhesion and Platelet Plug Formation d. Blood Clot Formation* (Adapted from Starr and McMillan 2013)

Lastly, during the coagulation phase clotting factors and procoagulants are released via the extrinsic and intrinsic pathways. These are reactions which occur in the vessel wall out with the bloodstream and inside the bloodstream respectively. These pathways combine to form prothombinase which acts to convert prothombin to thrombin. Thrombin then goes on to complete the clotting process by converting the plasma protein fibrinogen into strands of fibrin, producing a meshwork scaffold within the platelet plug. The red blood cells attach to this platelet-fibrin network (Figure 2.6), forming the blood clot stopping bleeding into the surrounding tissues

and producing the 'scaffold' required for vessel wall repair (Martini 2004; Wounds and Healing 2013).

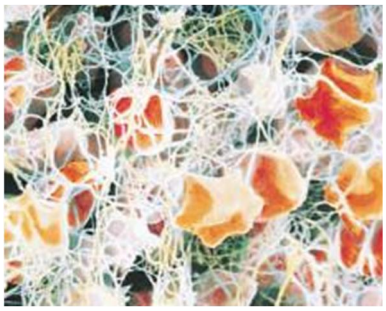


Figure 2.6: *Blood Clot, A Platelet-Fibrin Network With Attached Red Blood Cells* (Starr and McMillan 2013)

The rupture in the vessel wall is then repaired as the fibrin fibres pull and join the vessel walls back together. This causes the platelet plug to contract and be removed while smooth muscle and endothelial cells proliferate to complete the vessel repairs.

2.4.2 Degradation of Leaked Red Blood Cells

As the ruptured blood vessels repair, the red blood cells remain within the dermis and/or the subcutaneous tissues they have leaked into. This blood is what is visible on the skin as a bruise. Over time as the bruise heals, a colour change is observed, beginning with reds, blues and purples, changing to greens and yellows which go on to fade and disappear. The appearance of these different colours is a result of the accumulation of haemoglobin, found within the red blood cells and its subsequent degradation. Although it is difficult to state the exact time at which each of the colours appear and disappear, there is an accepted general colour order appearance for after a blunt force impact:

- Red – Immediately after impact.
- Blue – After a few hours.
- Blue/Purple – Approximately 2 days after impact.
- Blue/Black – Approximately 3 days after impact.
- Brown – Approximately 4-5 days after impact.
- Green – Approximately 5-7 days after impact.
- Yellow – Approximately 7-10 days after impact.

Once yellow is the only pigmentation visible, it will fade until the skin returns to its original colour. In total, the time taken from bruise appearance until it has completely disappeared is approximately 14 days however, this can vary between individuals. Figure 2.7 shows these typical colour changes and bruise disappearance over a period of 15 days (Dimitrova et al. 2006; Vij 2011).

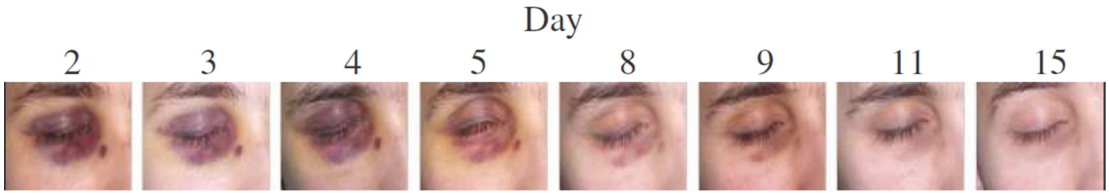


Figure 2.7: *Colour Changes Observed Within a Bruise Over 15 Days* (Dimitrova et al. 2006)

Haemoglobin is the red pigment of the red blood cell and is responsible for the initial red pigmentation observed within a bruise. Haemoglobin contains iron ions which give the molecule the ability to readily bind with oxygen, forming oxyhaemoglobin and carbon dioxide, forming deoxyhaemoglobin (Martini 2004; Dimitrova et al. 2006; Randerberg et al. 2011).

Macrophages (phagocytic white blood cells) are directed to the damaged vessels and are able to migrate from the bloodstream through vessel walls into the subcutaneous tissue and dermis. Here, these cells engulf the red blood cells and break them down into their component parts. The cellular proteins are broken down into amino acids which then become metabolised by the cell. The haemoglobin component has its oxygen and iron components removed, which are returned to the bloodstream to be applied in the formation of new haemoglobin molecules. The oxygen removal occurs more readily, hence why bruises begin to turn blue after a short period of time becoming darker in shade as more oxygen is removed. Some of the released iron can combine with the intracellular protein ferritin, producing haemosiderin. This compound is seen as the brown pigmentation within a bruise and is more commonly associated with the later stages of bruise development (no less than 72 hours after impact). The haemoglobin molecule, now absent of iron, is converted into biliverdin by the enzyme haeme-oxidase. This produces the green colours observed within a bruise as biliverdin is a green coloured pigment. As time progresses and more of the haemoglobin is converted, the levels of red, blue and purple tones diminish.

Biliverdin is then converted to bilirubin by biliverdin reductase. Bilirubin has an orangey-yellow pigmentation and as the last conversion it is commonly associated with older bruises which consist of more yellowy shades. The chemical conversion of haemoglobin to bilirubin is shown in Figure 2.8. (Martini 2004; Nash and Sheridan 2009; Randerberg et al. 2011).

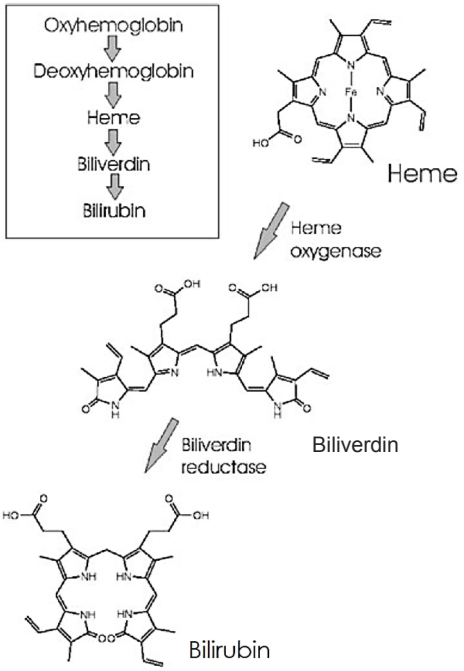


Figure 2.8: *Chemical Conversion of Haemoglobin to Bilirubin* (Randerberg et al. 2011)

The phagocytic cells then migrate back into the blood vessels, transporting the bilirubin into the bloodstream, causing the yellow pigmentation of the skin to fade and disappear. Here it binds to albumin within the blood and is transported to the liver where it is excreted within bile (Martini 2004; Randerberg et al. 2011).

2.5 Causes of Bruising

2.5.1 Blunt Force Impact

Bruises are formed as a result of a blunt force impact, i.e. an impact with a non-sharp surface, causing rupture of the underlying vessels (Figure 2.9). Such impacts can result from everyday falls or walking into objects such as furniture or doors. Furthermore, people who participate in contact sports (e.g. rugby or boxing), non-contact sports (e.g. squash or gymnastics) or activities such as paintballing would be

expected to suffer bruising as a consequence. This is due to the body tissues deforming with the impact, transmitting tensile, shear and/or compressive strains to the subcutaneous vessels, resulting in vessel rupture and thus bruise formation (Viano et al. 1989; Ko and Dang 2010; Hayward 2013).

2.5.2 Blunt Force Trauma

Blunt force trauma is the terminology used when a person has experienced a blunt force impact as part of a physical attack, for example aggravated assault. This can result in not only bruise formation but more extensive internal injuries (Ko and Dang 2010).

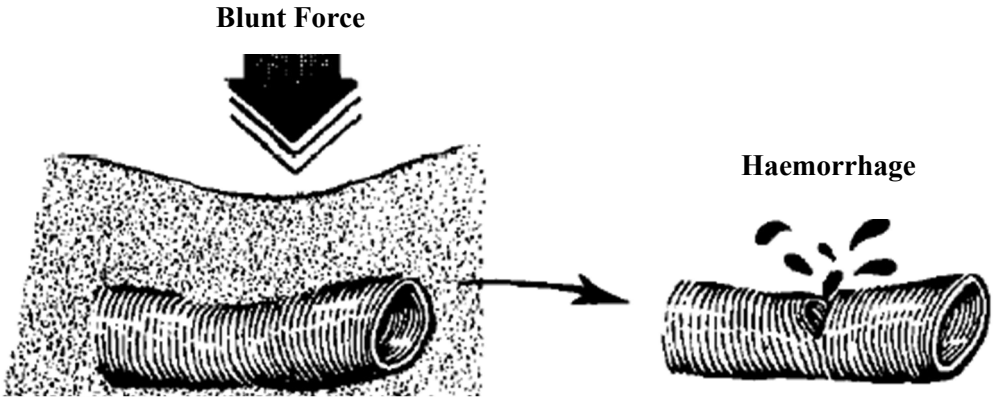


Figure 2.9: *Schematic of Vessel Rupture From a Blunt Force Impact* (Adapted From Viano et al. 1989)

2.6 Bruising Variances

Although the colour change observed within a bruise will generally follow the same pattern of red to yellow, the visual characteristics of a bruise are largely influenced by a number of factors. These factors are parameters of the impact, object characteristics, anatomical location of impact, physical build of the individual along with the presence of disease or if an individual is taking medication (Dimitrova 2006).

2.6.1 Impact Parameters

Both force and stress have a major influence on the appearance of a bruise. It is generally accepted that the greater these impact parameters are, a much larger and

deeper coloured bruise will be produced. Such parameters can also influence the rate at which the bruise forms. A greater force or stress could produce deeper bruising, thus the time for the blood to accumulate to a level visible on the skin surface will be longer than if a smaller impact was responsible. Bruises can reflect the object which produced them, thus the level of detail present if dependent on the force which is applied (Barnett 2007; Vij 2011).

Additionally, the level of force will effect whether a positive or negative image of the striking object is observed. For high impact forces a negative image of the striking object would be observed (i.e. a clear area surrounded by a bruise and possibly some petechiae). This is because the blood vessels have been stretched away from the striking object and torn during impact. Therefore, the blood is released away from the area of contact. In more forceful impacts a positive image of the striking object would be observed as the vessels are ruptured directly by the object (i.e. not stretched or torn). In this case a clear shape of the impacting object may be observed as the blood is released in the area of contact (Barber and Sibert 2000; Barnett 2007; Vij 2011).

Furthermore, the direction of impact will influence bruise shape, for example if a ball strikes perpendicular to the body a circular shape would generally be observed. However, if it were to strike at a more acute angle a more elongated oval shaped bruise would be observed. The duration of impact will also affect the visual characteristics as a longer impact would result in a greater skin deformation. Consequently, deeper vascular damage will result, thus producing a more extensive bruise (Barber and Sibert 2000; Vij 2011).

2.6.2 Object Characteristics

The shape and contact area of the impacting object will affect the shape of the bruise observed on the victim. Larger objects reduce the concentration of impact force on an area thus are less likely to cause injury. However, if a smaller object hits with the same force, greater injury would be observed as the impacting force is concentrated over a smaller area (Sadler, 1999).

Different impacting objects will produce different bruising patterns. If the body is struck by a rod like object, tramline bruising would be visible. This type of injury is characterised by two parallel bands of bruising encasing a central undamaged area of skin. This happens as a result of the underlying blood vessels being compressed, stretching the vessels causing rupture. Therefore, the bruising appears around the area of impact and not directly beneath it. The mechanism of this type of bruise formation is outlined in Figure 2.10 and an *in vivo* example is shown in Figure 2.11 (Sadler 1999; Bilo et al. 2013).

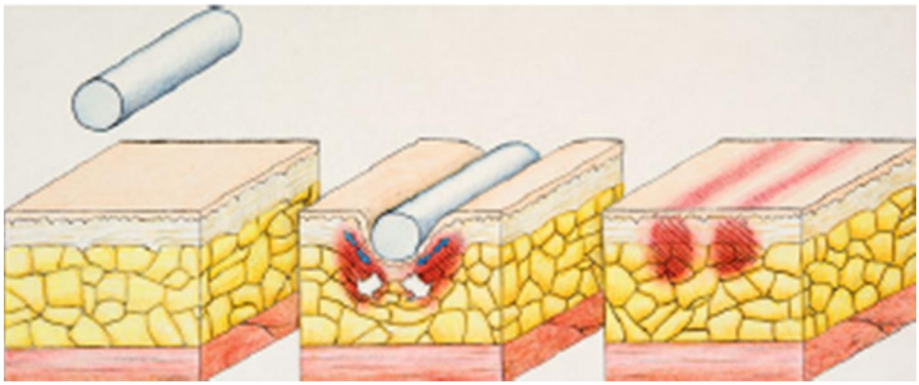
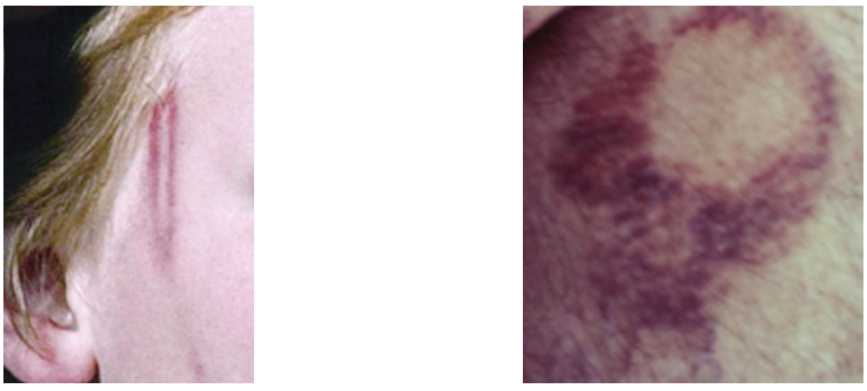


Figure 2.10: *Mechanism of Tramline Bruise Formation* (Bilo et al. 2013)

Doughnut shaped bruises result from an impact with spherical objects. Its formation is the same as that for tramline bruising however instead of two parallel lines, the undamaged zone in surrounded by a circular bruise. An example of this form of bruising is shown in Figure 2.11 (Sadler 1999).



a. **b.**

Figure 2.11: *Examples of Bruise Shapes - a. Tramline Bruise b. Example of a Doughnut Shaped Bruise* (Bilo et al. 2013; Hunt 2007)

In cases where there has been forceful, physical restraint to an individual (i.e. the impacting object is another person's hands), finger pad bruising will be present on

the victim. These are round or oval shaped and will appear slightly larger than the fingertips which caused them. This is because the blood from the ruptured calls spreads outwards creating a larger bruised area. An example of this form of bruising is shown in Figure 2.12. If an individual is restrained against a surface such as the ground or a wall, counter pressure bruising would be formed. These bruises appear over areas with bony prominences such as the back or the shoulder blades (Sadler 1999).

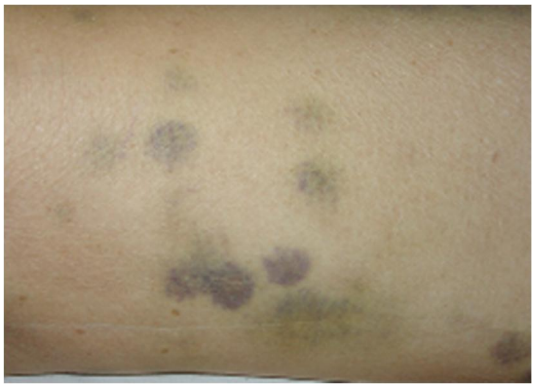
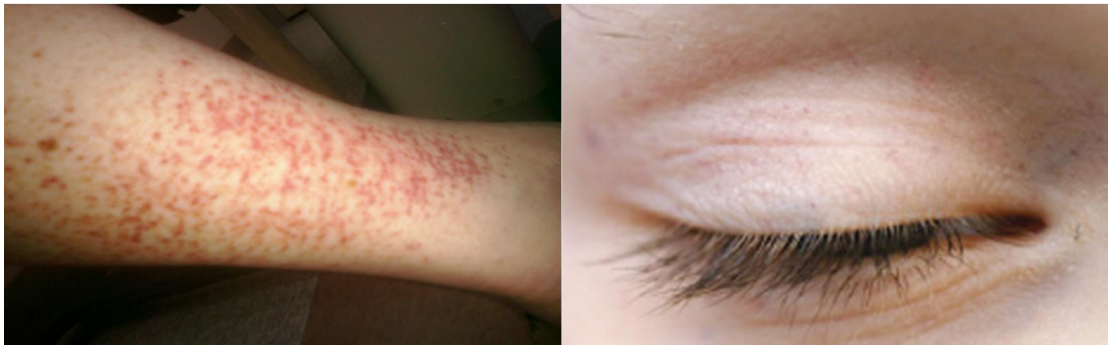


Figure 2.12: *Example of Finger Pad Bruising* (Palmer, Brodell and Mostow 2013)

Petechiae (Figure 2.13) are small, pinprick sized bruises (< 2mm) and can appear similar to a rash. They can reflect the texture of clothing which has been forced against the skin and appear circular in shape with regular sizing. They can also be present surrounding bruising caused by a car tyre, sole of a shoe or ligature restraints. However, they do not necessarily result from a blunt force impact. Petechiae can be explained through changes in blood pressure which damages the walls of small blood vessels (capillaries), causing them to rupture, for example if a person is subjected to strangulation (Stephenson 1995; Payne-James, Crane and Hinchliffe 2005; Dimitrova et al. 2006; Cox 2011; Vij 2011; Bilo et al. 2013).



a. **b.**

Figure 2.13: *Example of Petechial Bruising – a. Petechial Bruising on the Leg b. Petechial Bruising Around the Eye* (Cox 2011; Bilo et al. 2013)

2.6.3 Anatomical Influences

There are many anatomical features which can influence the appearance of a bruise, hence why an impact of the same force on the same area of the body can form varying bruises between different people.

2.6.3.1 Build

Individuals who are more athletic or have a more muscular build are less likely to bruise as their blood vessels are protected by their musculature. In comparison, individuals with a greater body weight (particularly the obese), will bruise much easier as they have a greater amount of subcutaneous tissues containing unprotected blood vessels (Sadler 1999; Vij 2011).

Sex of an individual also has an effect. In general, females contain a greater amount of subcutaneous tissues than males, thus will have a greater tendency to bruise (Sadler 1999; Vij 2011).

2.6.3.2 Location and Migration

The level of support to the skin varies with location on the body. Looser tissues will generally form larger bruises as there is space within the subcutaneous layer for blood to accumulate. Locations of such tissues are the eyelids, face and genitalia. In comparison, strongly supported areas of skin will present with smaller sized bruises. This is as the dermis is thicker and the tightly packed tissue prevents large accumulations of leaking blood. Furthermore, location of impact and the gender of

the individual are interlinked in affecting the visible characteristics of a bruise. The distribution of the subcutaneous tissues differs between males in females thus areas which bruise easily in females will not necessarily be the same for men. In men, subcutaneous tissues are prominent in the arms, neck and lower back. However, in women these tissues are most prominent in the thighs, hips and breasts (Vij 2011; Martini 2004).

The location of an impact will also influence where the resultant bruise appears. Within the looser tissues, the blood released from ruptured vessels can be subject to the effects of gravity. An example of this is someone who appears to have a black eye (also known as a peri-orbital haematoma). As well as resulting from a direct impact to the eye area of the face, it can also be caused by an impact to the forehead. The released blood travels downwards via a path of least resistance, accumulating in the eye area, hence the formation of a black eye (Figure 2.14). Another example is where an individual forms a bruise in their thigh after experiencing an impact to the pelvic region (Sadler 1999; Vij 1999).

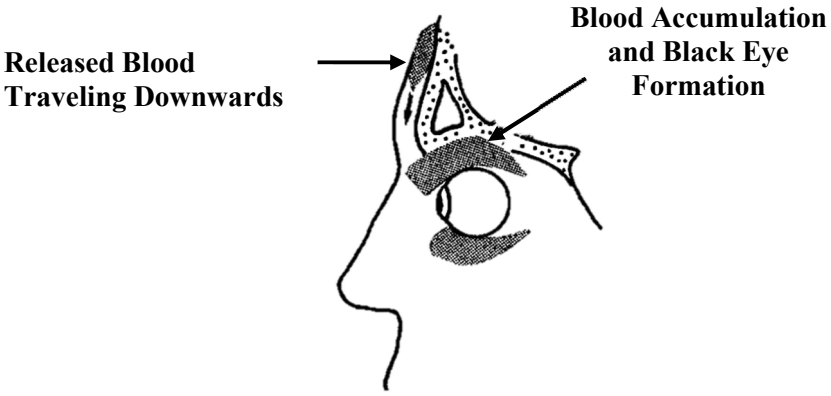
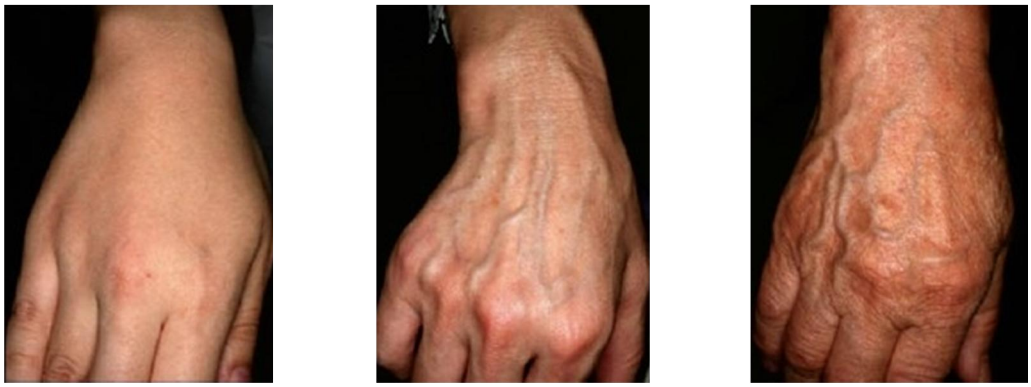


Figure 2.14: *Black Eye Resulting from a Blunt Force Impact to the Forehead* (Adapted From Payne-James, Crane and Hinchliffe 2005)

2.6.3.3 Age

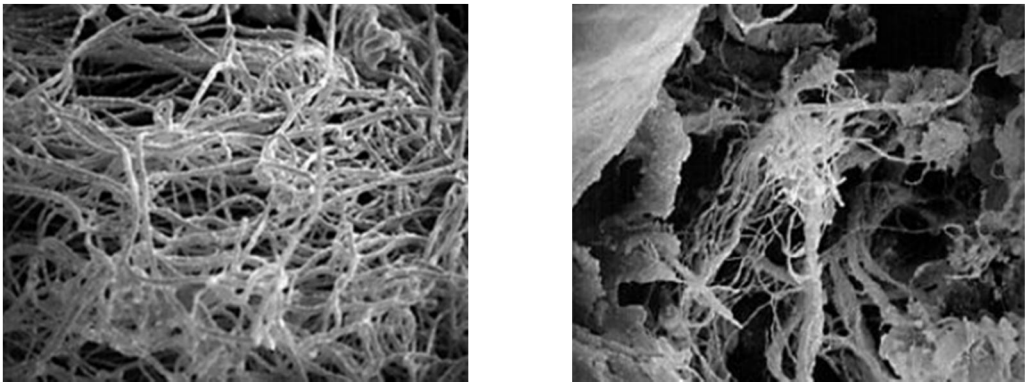
The age of an individual is very influential in bruise formation. Young children bruise easily due to their greater subcutaneous tissue layer and delicate skin. As an individual reaches adulthood, the fatty tissues redistribute and their ability to bruise reduces as muscle content increases. This provides protection to the underlying vascular system. The elderly bruise very easily in comparison to adults due to a loss in the supportive connecting tissues (i.e. the collagen fibrils) of the skin (Figure 2.15

and Figure 2.16) and degradation of blood vessel integrity (Sadler 1999; Kruger et al. 2010; Vij 2011).



a. **b.** **c.**

Figure 2.15: *Loss of Supportive Connective Tissues of the Skin With Age – a. 20 year old b. 50 year old c. 70 year old* (Adapted from Ono 2011)



a. **b.**

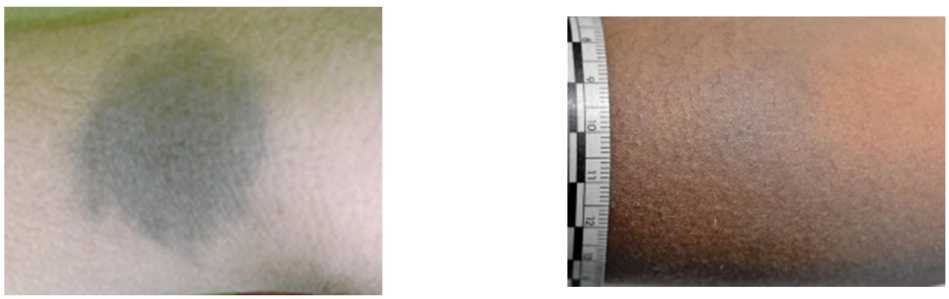
Figure 2.16: *Changes in Collagen Fibril Content With Increasing Age – a. Content Within a Young Individual b. Decreased, More Densely Packed Content Within an Older Individual* (Kruger 2010)

Furthermore, the elderly are more likely to be taking medication which can affect their bloods ability to clot, thus more extensive bruising will likely be observed (Sadler 1999; Vij 2011).

2.6.3.4 Skin Colour

Skin colour does not affect bruise formation but the visible characteristics of the bruise. Skin pigmentation is controlled by the melanin compound within the skin. It can be split into two types. The first, pheomelanin, is a red pigment found in feathers and hair, is associated with people with the genetic trait of red hair. Eumelanin is the most abundant form and is a brown-black pigment responsible for skin colour. The degree of skin pigmentation is dependent upon the number of synthesizing cell organelles (melanosomes) and their level of distribution throughout the epidermis of the skin. It has previously been shown that for dark skin colours, these organelles make up 18-43% of the epidermis, for moderately dark skin 11-16% and for pale caucasian skin 1.6-6.3% (Angelopoulou 1999).

On caucasian skin, a bruise is easily spotted and the colours present over time are easy to see. However, on darker skinned individuals colours may be masked as there is not as great a contrast between the bruise and the skin pigmentation. Furthermore, bruise shape and size can be unclear due to this lack on contrast. The difference in bruise visibility is shown in Figure 2.17 (Sadler 1999; Vij 2011; Thavarajah, Vanezis and Perrett 2012).



a. **b.**

Figure 2.17: *Comparison of Bruising on Different Coloured Skin – a. Bruise on Caucasian Skin (Clear Contrast) b. Bruise on Dark Skin (Unclear Contrast)* (Bilo et al. 2013)

2.6.3.5 Medical Conditions and Lifestyle

2.6.3.5.1 Medical Conditions

Some people will bruise more readily than others due to the presence of a medical condition, such as a coagulation or platelet disorder. Such conditions result in an individual experiencing large bruising (greater or equal to the size of an orange), in response to minor or no trauma. Examples of some conditions and how they influence bruise appearance are listed below (Konkle 2006; Spinks 2007; Hayward 2013).

Ehlers-Danlos Syndrome – a genetic disorder which affects the body's connective tissues, including collagen. This reduces the integrity of the tissues that holds skin, bones and blood vessels in place and therefore blood vessels are prone to tearing (Kelly 2013).

Cushing's Syndrome – a disease of the adrenal cortex which results in excessive levels of glucocorticoids (steroid hormones). This reduces the body's ability to metabolise carbohydrates and fats, thus results in weight gain. Reduced muscle mass is also a symptom, hence why blood vessels are easily damaged (Brooker and Nicol 2011).

Scurvy – a disorder resulting from a lack of vitamin C. This reduces the body's ascorbic acid levels and thus reduces the formation of collagen. As a result, the integrity of the skin and blood vessels is reduced, resulting in purpura being present (small, rash-like marks, similar to petechial bruising) (Hirschmann and Raugi 1999).

Schamberg's Disease – an inflammatory skin condition where blood vessels become damaged, thus causing blood to leak out into the surrounding skin. This produces an orangey-brown discolouration similar to the appearance of an older bruise (Billings and Cotton 2011)

Von Willebrands Disease – an inherited bleeding disorder. This disease is characterised by a deficiency in the von Willebrand factor and clotting factor VIII, which increases the time taken for blood to clot. The disease also

impairs platelet function, hence why bruising is a common symptom (Robinson 2013).

Idiopathic Thrombocytopenic Purpura (ITP) – an autoimmune disorder which reduces platelet production. As one of the most common bleeding disorders, it can be diagnosed if an individual has a recent history of unexplained bruising. This is due to the reduced levels of platelets, affecting the body's ability to efficiently repair damaged blood vessels (Bolton-Maggs 2000; Chu, Korb and Sakamoto 2000; Andrès et al. 200).

2.6.3.5.2 Medications

Prescribed medication can influence an individual's tendency to bruise. Anticoagulation and antiplatelet medications will increase bruising as they reduce the body's ability to repair ruptured vessels. Anticoagulants such as warfarin, heparin, dabigatran and phenindione work by interfering with the production of clotting factors and form blood clots. Antiplatelet medications such as aspirin, clopidogrel and dipyridamole instead work by reducing platelet production or platelet stickiness, thus preventing repair of damaged vessels. People who are likely to take such medication include those who have mechanical heart valves, peripheral vascular disease joint replacements or those at risk of stroke and heart attack (Whitehall 2012; Kenny 2012).

Corticosteroids, commonly known as steroids, are used as an anti-inflammatory treatment. These drugs can thin the skin, weaken connective tissues and reduce muscle strength, thus reducing the protection to underlying blood vessels. Other medications such as quinine (used for malaria treatment) can trigger ITP, while any drug which has the potential to cause liver disorders can indirectly cause coagulation problems (Spinks 2007; BNF 2013; NHS 2013).

2.6.3.5.3 Lifestyle

Diet will influence an individual's build via levels of subcutaneous tissues. However, if food supplements are incorporated into an individual's diet they can have an anti-coagulant effect. Supplements such as ginkgo biloba, fish oil, garlic and ginger have

been found to have such an effect. Herbal remedies are also reported to affect blood coagulation (Spinks 2007; Vij 2011).

If an individual lives in an environment where they are exposed to high levels of sunlight, the integrity of the skin may be reduced further increasing their tendency to bruise. Furthermore, if an individual is a smoker, skin integrity is also affected (Vij 2011; Randerberg et al. 2011).

Another influential lifestyle factor is alcohol intake. Chronic alcohol abuse directly reduces platelet function and by also instigating liver disease, reduces the bloods ability to clot. Therefore, those suffering from alcoholism will have a higher tendency to bruise in comparison to those who do not (Spinks 2007).

3 Impact Biomechanics of the Human Body

3.1 Definition of Impact Biomechanics

Impact biomechanics research into human injury aims to understand the processes and effects of impact stresses generated in and on the body as a result of a forceful impact. Understanding the biomechanical features of a blunt force trauma is useful in the forensic reconstruction of a trauma event, providing insight into the time of injury, force of impact and weapon used. (Viano et al. 1989; Whittle et al. 2008).

3.2 Mechanics of Impact

Impact injuries are a result of excessive deformation of biological tissues beyond their threshold of recovery, causing anatomical and/or physiological damage. The deformation is generally associated with blunt force impacts and is measured in terms of strain, i.e. the level of change in dimension and can be described as either tensile, shear or compressive. If tensile or shear strains go beyond the strength of the biological tissue, injuries such as lacerations, ruptures, fractures or avulsions may result. Compressive strains will produce injuries associated with crushing forces such as fractured bones (Viano et al. 1989).

The risk of injury from an impact is related to the kinetic energy being transmitted to the body and object shape. If the object is moving at a high velocity, such as a bullet from a gun, or is moving at a slower rate but has sharp impacting surface, the object is likely to penetrate the skin producing laceration injuries. This is due to the kinetic energy from the object being transmitted over a small area. Thus, a small impacting area means that the applied energy has minimal opportunity to dissipate through the tissues, producing more significant structural damage (Viano et al. 1989; Cox 2011).

For blunt force impacts, the kinetic energy is distributed over a much larger area (as the impacting area of the object is significantly larger), thus it can be absorbed by the underlying subcutaneous tissues. This gives the affected surfaces time to deform, extending the impact time, reducing the severity of the injuries produced (Viano et al 1989; Cox 2011).

3.3 Skin Biomechanics

Although the skin is composed of 3 distinct layers (epidermis, dermis and subcutaneous layer), each of which have their own individual mechanical properties, they all react in unison (i.e. like a monolayer) when an external force is applied. Skin behaves as an anisotropic (direction dependent), non-homogenous and non-linear viscoelastic material when subject to mechanical loading, giving skin its characteristic function of protecting the internal organs of the body. The skin's viscoelastic properties are dependent upon the structure of the extracellular matrix (i.e. the proteoglycan and water content), and also the structure of the elastic and collagen fibres within the dermis. As a result, modulus of elasticity of skin changes with time and with different experimental conditions (Silver, Freeman and DeVore 2001; Boyer et al. 2007; Kieser et al. 2008; Kruger et al. 2010).

3.3.1 Viscoelastic Response

When subject to mechanical loading, skin shows two components of response: the viscous and elastic components. The viscous component is associated with the dissipation of the impacting energy. Dissipation is achieved by the viscous sliding of the collagen fibres of the skin, as they align with the direction of the external force. These changes in fibre orientation is what is responsible for the skin's ability to deform without being damaged, as the greater the level of force applied causes the skin to progressively become stiffer. The elastic component is responsible for the skins ability to return to its original shape after being deformed. As a result, these viscoelastic properties dictate how the rate of impact determines the resultant contact pressure produced as the reduction and dissipation of such forces depends upon the fluid content of the skin (Purslow, Wess and Hukins 1998; Silver, Freeman and DeVore 2001; Keiser et al. 2008).

3.3.1.1 Collagen Fibre Rearrangement

When subject to large strains, the collagen fibres become three times as stiff as the elastin fibres within the skin, hence their role in controlling skin stiffness. It has been said that in general, collagen fibres only support tensile loading. This explains why in

tissues such as the skin, fibre reorientation occurs (Annaidh et al. 2012; Nagel and Kelly 2010).

Studies which best highlight the rearrangement of collagen fibres are those looking at collagen gels as a cellular scaffold. Robertson et al. (2013) stressed cellularised collagen gels by compacting them around a solid mandrel. The mandrel was then removed and the circular gel cut, removing both internal and external stresses. The images taken of the fibres show the stressed parallel fibres becoming randomly orientated once all applied stresses have been removed (Figure 3.1).

a. **b.**

Figure 3.1: *Effect of Stress on Collagen Fibre Orientation – a. Stressed Collagen Gel, Organised Collagen Fibres b. Unstressed Collagen Gel, Unorganised Collagen Fibres* (Adapted From Robertson, et al. 2013)

3.3.1.2 Stress-Strain Response

The typical stress-strain response for skin can be divided into three phases, the first of which is the loading phase. In this phase the skin undergoes a large deformation for the lower levels of stress. The collagen fibres at this point are mostly unaligned, hence the large deformation. Going into the second phase of the stress-strain response, skin stiffness steadily increases as the fibres align themselves with the applied load. The third phase of the response is the most linear section. The majority of the collagen fibres are in alignment with the load, causing a rapid increase in skin stiffness (Annaidh et al. 2012).

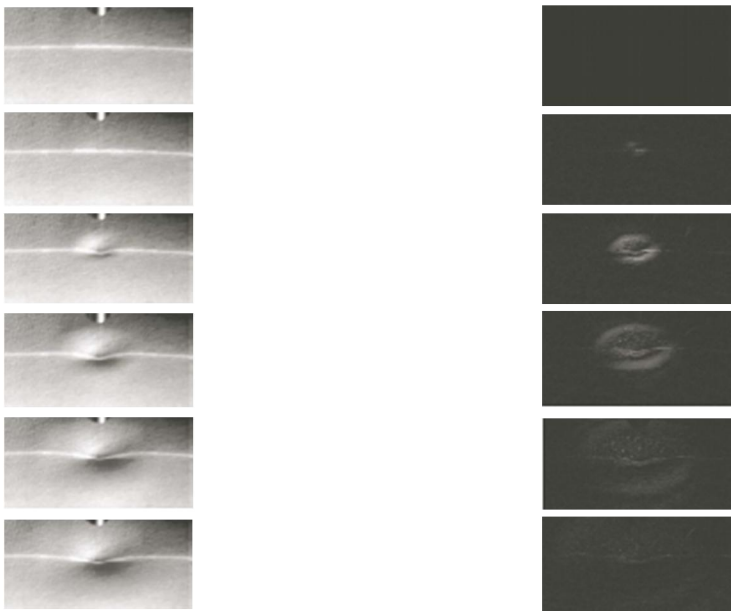
As the skin is a large organ, the level of stress required to rupture a small area will equal that required for a large area. However, for a larger area, a greater impacting force is required to achieve the damaging stress levels. This means that in cases of a blunt force impact, the impacted area of skin is able to reduce the applied force by elastically stretching. Therefore, the applied stress is dissipated and skin rupture is prevented. The skin's ability to undergo stretching (or large strains), is referred to as resilience (Kieser et al. 2008).

3.3.2 Skin Surface Response to Blunt Force

It has been suggested that a high velocity blunt force impact will produce a deformation which spreads through the tissues, producing localised changes to the tissue's stress and strain properties (Whittle 2008).

When a blunt force impact strikes the body, an unbalanced force is produced. As this force is reduced, the viscoelastic properties of the skin return the altered tissue back to its original state through the production of a transient deformation. This deformation begins at molecular level where intermolecular forces within the skin causing the impacting object to decelerate. The deformation then increases, becoming visible on the skin surface as a 'shockwave' or 'tissue wobble' (Figure 3.2). As the skin is able to move independently of the skeleton, it plays a role in the dissipation of impact forces to protect the body (Viano et al. 1989; Pain and Challis 2001; Pain and Challis 2002; Challis and Pain 2008).

It has also been stated that the underlying muscles will affect the skin's response to an impact. If tensed up in anticipation of an impact, this causes the muscles to become much stiffer. As a consequence, the impacting force is increased due to a greater deceleration, but its duration is decreased. Furthermore, the skin's deformation in response to the impact occurs at a faster rate. This implies that tense musculature provides greater protection for the body by influencing the skin's response (Pain and Challis 2002).



a. **b.**

Figure 3.2 : *Skin 'Shockwave' Propagation Induced by an Air Jet, a. Original Image b. Skin Shock Wave* (Adapted From Tanaka and Kaneko 2006)

4 Forensic Documentation of Bruise Injuries

4.1 Recording of Bruise Injuries

Forensic photography is essential for the recording of physical injuries as evidence. In general, physical injuries such as bruises are only photographed in cases of serious crimes (e.g. domestic violence, rape or aggravated assault), rather than minor assault offences. At the time of a serious crime being reported, photographs taken by a police officer using a camera phone are accepted as short term documentation, before arrangements can be made for a Scene of Crime Officer (SOCO), to photograph the injuries as official records. Both close ups and normal distance images should be taken at various angles including at 90˚. This ensures that the extent of bruising cannot be exaggerated or misinterpreted from the images at a later date (Özkalipci and Volpellier 2010; Black 2013).

4.2 Detection and Documenting Techniques

4.2.1 Digital Photography

Digital photography is the standard method of image capture of any piece of physical evidence. Unlike film photography which uses a light sensitive film, digital photography uses many light sensitive picture elements (also known as pixels), as part of a sensory chip to collect an image. These pixels allow for higher levels of detail to be collected, with the level of detail being dependent upon the number of pixels within the camera. The collected images have the advantage of having multiple storage options: the flash card/memory device within the camera, digital computer file and/or a paper printout. Furthermore, digital photography allows for light exposure to be controlled at the point of capture and also to be manipulated via computer processing (Blitzer and Jacobia 2002; Blitzer, Stein-Ferguson and Huang 2008).

4.2.2 Imaging Techniques

Digital photography also allows for different imaging techniques to be used. The electromagnetic spectrum of light ranges from ultraviolet (UV), at wavelengths of 200-375 nm, visible at 400-700 nm and infrared (IR), at 700-900 nm and each range penetrates the skin at different levels (Figure 4.1).

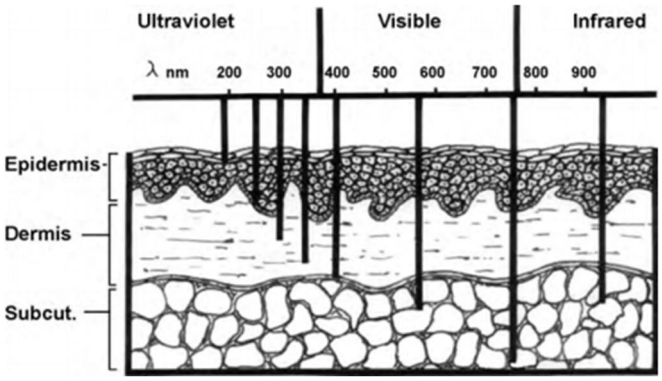


Figure 4.1: *The Levels of Penetration for the Different Wavelengths of the Electromagnetic Spectrum* (Wright and Golden 2010)

When light hits the skin, reflection, absorption and fluorescence occur. Reflection occurs as the shorter wavelengths of light have very little penetration into the skin, thus are reflected away. Absorption occurs as longer wavelengths of light penetrate the skin, up to 3 mm depths, thus do not reflect. Fluorescence results from light increasing the resting energy of molecules, i.e. molecular level excitation occurs (Rai and Kaur 2013).

4.2.2.1 Visible Light

For photography of bruises, a visible light (also known as white light or colour), photograph is always taken. This image represents the spectrum of light the human eye can see, for example blues are visible at wavelengths of 420 nm and reds from 650 nm (Figure 4.2) (Tetley 2005; Rai and Kaur 2013).

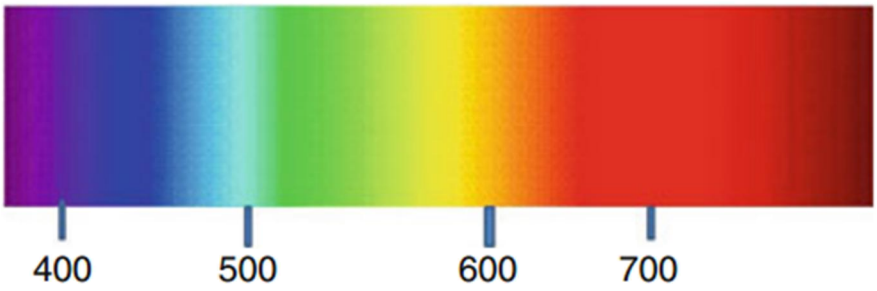


Figure 4.2: *Spectrum of Visible Light* (Rai and Kaur 2013)

Visible light images document physical injuries as they appeared at the time of incident or after a period of time, providing information on the range of colours present. However, the levels of colour which can be detected by a visual light camera can be greater than those which can be perceived by the human eye (As shown in Figure 4.3). Thus colour images can reveal characteristics which originally could not be perceived. These types of images are what are commonly used in the forensic interpretation of bruising (Tetley 2005; Rai and Kaur 2013; Wright and Golden 2010).

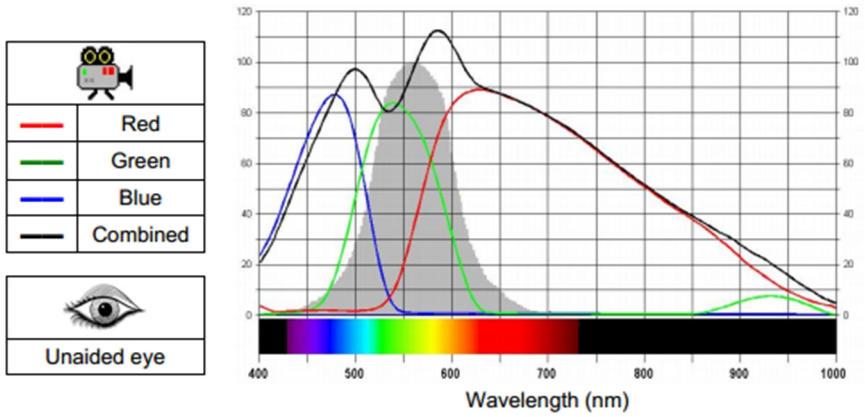


Figure 4.3: *Spectrum of RGB Combined and Individual Wavelengths as can be Detected by a Camera and the Naked Eye* (Foster + Freeman 2012)

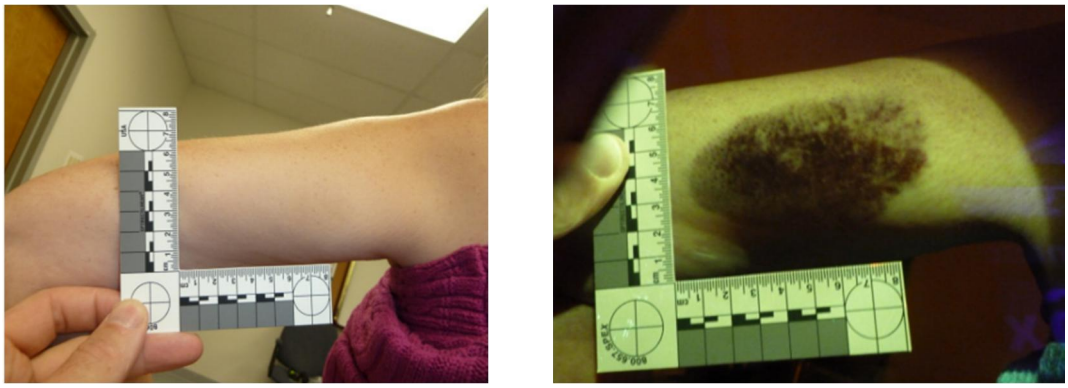
4.2.2.2 UV and IR

By using a camera containing filters which allow image capture within the non-visible spectrums (UV and IR), previously non-visible injuries and injury patterns can be detected. UV light has very little penetration into the skin hence its use is generally to provide more definition to the surface details of an injury. For example, it can produce an image of a bruise with a more defined edge, thus giving an idea of the shape of the impacting object. IR imaging has the potential to detect any bleeding

much deeper within the tissue than UV or visual light can. Furthermore, oxygenated blood which would be present nearer the time of impact reflects IR light, whereas deoxygenated blood will absorb IR. Therefore, the resultant IR photograph could be used to indicate the age of a bruise (Rai and Kaur 2013; Tetley 2005; Wright and Golden 2010).

4.2.2.3 Alternative Light Source

In the detection of the fluorescence produced by light impacting the skin, alternative light source imaging (ALS) (narrow-band illumination), is used. In forensic applications, it has been shown to differentiate between healthy and bruised skin on an individual (Figure 4.4), whilst also having applications in the detection of fingerprints, bodily fluids and trace metals. ALS works by illuminating the skin with light with a wavelength of 450 nm. The light that is absorbed may be re-emitted at a larger wavelength, thus filters or goggles are used to differentiate it from the applied light. Therefore, ALS imaging allows for the visualisation of faint or non-visible bruising (West, Hayne and Barsley 1996; Hughes, Ellis and Langlios 2006; Rai and Kaur 2013; Deutsch et al. 2013).



a. **b.**

Figure 4.4: *Bruised Inside Arm – a. Arm Under Visible Light b. Arm Under Alternative Light Source* (Deutsch et al. 2013)

4.2.2.4 VSC

The Video Spectral Comparator, or VSC, is a lighting instrument which uses a variety of different light sources at several different wavelengths. It is commonly used in questioned document analysis where IR, UV and narrowband imaging (i.e.

over a narrow wavelength of light), can be employed along with various filters, such as red, green and blue filters. This allows for the security features on passports or banknotes to be visualised when examining for counterfeits (Staffordshire University 2011).

This instruments ability to switch between lighting sources and ability to record images of these wavelengths without specific environmental conditions means that it could be employed in the detection of bruises. However, this would most likely only be appropriate when examining an individual's arms and possibly legs as it is not a portable instrument.

5 Forensic Bruise Analysis

5.1 Current Expert Visual Analysis

The current standard method of visual assessment of a bruise is regarded as extremely unreliable as it is highly subjective. There have been various studies which have assessed the effectiveness of visual assessment and have found it to be inaccurate and inconsistent. Due to their relevance to this investigation, some of these studies are detailed below.

5.1.1 Colour Development of Bruising

Studies by Langlois and Gresham (1991) and Dimitrova et al. (2006) provide a review of previous publications looking into the varying opinions on the timeline and colour development of a bruise. Langlois and Gresham highlighted that some had the view that bruising became visible almost immediately, while others stated that visualisation would take up to 24 hours after impact. Furthermore, it was found that although most stated that for complete resolution of a bruise it would take approximately 2 weeks, other publications said that resolution could take up to a month.

Dimitrova et al. provided a more extensive review of 16 papers on the expected colour changes within a bruise over time periods up to 2 weeks. For the papers which detailed the changes over each of the total 14 days, the range of colours followed a general pattern. The papers agreed that the levels of red were most prominent in the early stages of bruise development, decreasing with increasing levels of yellow. However, there was little agreement on the timings and presence of other colours including blue, purple, black, brown and green. This therefore highlights how varying opinion on apparent colours will influence the accuracy in bruise age estimation, when using visual colour analysis alone.

5.1.2 Professional Experience and Important Bruise Characteristics

Grossman et al. (2011) aimed to investigate if the number of years of forensic experience was an influential factor in accurate bruise age estimation, whilst

identifying the properties which were used by forensic experts during the bruise assessment.

A total of 23 forensic experts participated in the study and were asked to estimate the age of 25 bruises presented in photographs. The experts were members of one of three groups: 1. qualified nurses, clinicians and paramedics; 2. police and forensic medical examiners who participated in forensic work; and 3. members of the Essex Medical and Forensic Services who provide clinical and medical forensic services to the police service. The years of experience ranged between 0 to greater than 5 years. As well as age estimation, each expert was asked to state which characteristics and colours of the bruise they found to be most useful to them and rank their importance in order of relevance.

Of the total 575 age estimations made, only 4 were found to be correct. It was found that a majority of 320 results were overestimated, while the other 250 were underestimated. Statistical analysis of the results also showed that as the years of experience increased, the accuracy of age estimation did not increase. These findings highlight the unreliability of expert visual assessment of bruises and also how the experience of an expert does not give them a greater ability to assess bruises accurately.

From the data collected on important bruise characteristics, it was shown that all 23 experts valued colour as the most important, with the presence of yellow being the most significant followed by red, purple, blue, green and brown. Intensity of bruise colour and size of the bruise were identified as being useful, with texture of the skin, swelling and the presence of a distinct edge also being considered. These findings highlight the variance in what characteristics used to assess bruise age and the lack of standard assessment criteria. Furthermore, the study found that some experts went on a ‘gut feeling’, which further highlights the flaws in visual assessment and how assessment process is entirely opinion based.

5.1.3 Health Professionals and Bruise Colour Assessment

Munang, Leonard and Mok (2002) carried out a study where 3 health professionals (a doctor, nurse and medical student), were asked to describe which colours they perceived in 58 bruises. The assessment consisted of two stages, where each participant was asked to describe the colours they perceived in each bruise while *in vivo* on child volunteers (recruited from an Accident and Emergency Department of an Edinburgh hospital). After the initial assessment, colour photographs of the bruises were taken and presented to the same 3 professionals at a later date to describe a second time.

Of the 58 bruises observed *in vivo*, only 6 were in complete agreement between the 3 observers. This meant that there was either a complete colour match (e.g. yellow stated by all observers), basic colour agreement excluding the shade of colour (e.g. dark red and light red) and agreement on two colours when two are mentioned (e.g. greenish-blue and bluish-red) between all observers. For the same 58 bruises, when describing the colours present from photographs, only 4 bruises were found to be in complete agreement. The colour observations for both *in vivo* and the photographs were compared and only 1 description was in complete agreement between the 3 observers.

This study also compared the level of agreement in colour perception between the *in vivo* and photographed bruises for each observer, between the three observers. This produced a total of 174 observations. Of this total, 54 were found in complete agreement, 79 in partial agreement (i.e. agreement on at least one colour when two have been mentioned) and 41 in no agreement. Furthermore, the study found that in these 174 comparisons 42 included the presence of yellow and of these, only 13 were in agreement between the *in vivo* and photograph.

Munang, Leonard and Mok also raised the concern with visual assessment by experts where they are presented with a photograph rather than an *in vivo* bruise as the photograph can be misleading. The 2D image loses any contours or swelling associated with a bruise. Thus, if an expert bases their opinion upon these characteristics, their interpretation will be inaccurate.

The study focused on health professionals rather than forensic experts however, its findings highlighted the inaccuracies of human colour perception and thus how this effects an individual's interpretation.

5.1.4 Prediction of Bruise Age Through Physical Examination

An investigation by Bariciak et al. (2003) aimed to determine if it is possible to predict the age of a bruise via physical examination. A total of 16 emergency physicians, 8 other qualified physicians and 39 trainee physicians were asked to take part in assessing 42, 17 and 38 bruises respectively. There were a total of fifty bruises used, located on children up to the age of 18 who were enrolled from the emergency department of a children's hospital.

Each of the observers were asked to complete a form for each bruise, indicating the bruise's location, observable colours, any other signs of injury (e.g. abrasions or swelling), the estimated age of the bruise and what factors influenced their estimation.

The percentage of observers in each group able to estimate the age of the bruises within 24 hours of its true age did not reach above 50%. The highest percentage of accurate estimations, 47.6%, was made by the emergency physicians. The percentages of accuracy for the other physicians and the trainee physicians were 29.4% and 36.8% respectively, indicating the level of training does not increase age estimation accuracy.

The study also found that there were three main characteristics used in the determination of bruise age. These were colour and swelling, colour and tenderness and colour alone however, the group of other professional physicians did not state colour and swelling as an influential factor. Furthermore the degree at which each of these factors was considered influential varied between each of the groups.

Their results also stated that although colour was the most influential factor in all the observer's estimations, there was little agreement on which colours were present.

Although limited in the number of bruises observed by all three groups of observers (only 13 in total), the study highlights the inconsistencies in the visual interpretation of bruises.

5.1.5 Influence of Human Colour Perception

Although there is a wide range of opinions on which colours should be used in the aging of a bruise, it is widely accepted that the colour yellow is significantly important as it is only found within older bruises (> 48 hours) (Maguire et al. 2005).

In 2004, a study by Hughes, Ellis and Langlois investigated the level of colour perception. A total of 50 volunteers with normal colour perception were shown various images of a bruise, which had been digitally altered to contain increasing percentages of yellow (0% - 20%). Once each volunteer stated they could see yellow within the image, the percentage was recorded. The ages of the volunteers ranged from 21 to 53 years.

The study found that perception ranged between 4% and 16% yellow concentration with a mean value of 8.6%. As the images had been digitally altered making them standardized and it was stated that other influential variables such as illuminating light were controlled, the variances in colour perception must result from the individuals themselves.

The study acknowledges that this could result of genetic variations in the photoreceptor genes. Furthermore, observer age influences colour perception. The study referenced a previous study which it is documented that the threshold for the perception of yellow in a 25 year old was 2% less than that for a 65 year old. The investigation by Hughes, Ellis and Langlois involved observers with a mean age of approximately 35 years, thus their results were influenced by observer age.

Their investigation highlights how inconsistent visual colour discrimination is by the human eye and how the level of discrimination is influenced observer variances in age and genetics. Therefore, it is clear that visual expert interpretations of a bruise will be inaccurate and that the level of colour perception will undoubtedly vary

between experts. This further indicates the issues surrounding bruise colour perception on victims of varying skin colour.

5.2 Improving Bruise Analysis

To rectify the issues surrounding visual analysis of bruises, various techniques have been tried. A selection of studies which have proposed such techniques are discussed within this section.

5.2.1 Colourimetric Scales

To address the unreliability of using photographs for the interpretation of bruise age, Nuzzolese and DiVella (2012) proposed the use of colourimetric scales.

There were two proposed scales, each L-shaped with one including a 6cm scale. Both consist of black and white circles which can be used for colour calibration via computer photo-editing, together with the colour variations of dark red, bluish, purple, greenish, yellow and light brown (Figure 5.1).

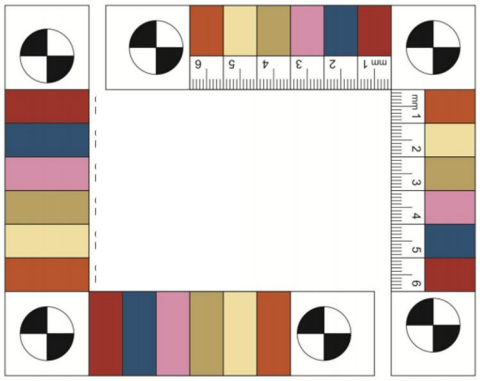


Figure 5.1: *Two Colourimetric Scales* (Adapted From Nuzzolese and DiVella 2012)

In terms of improving the reliability of photographic documentation of bruise injuries, the concept of a colour scale is a good idea. It provides the ability to standardize all photos to the same level thus eliminating any variation produced from the lighting conditions and type of camera used.

However, they chose the colours for the scale from a literature review of visual assessment of determining bruise age. This meant that it only focused on specific colour models such as RGB and CMYK (cyan, magenta, yellow and key (black)),

and does not acknowledge the variance between individuals colour perception. Another disadvantage is that it is only designed for use on caucasian skin, limiting its use. Furthermore, although designed to aid bruise age estimation, the study states that time intervals of 2, 5 to 7 and 14-15 days would be used. Therefore, the ability to derive an accurate time of injury is impossible.

5.2.2 Spectroscopy and Computer Modelling

Kim et al. (2012) aimed to understand the changing composition of aging bruises using a combination of spectroscopy measurements and computer modelling.

They recorded the concentrations of bilirubin, blood oxygenation and blood volume fraction using spectrometry, showing that their levels would peak at various stages throughout the bruise timeline. Specifically bilirubin peaked at 80 hours and this value along with those for the other parameters were then applied in the formation of a computer model. This model represented the epidermis, dermis and subcutaneous tissue layers of the skin.

The use of spectroscopy has the advantage that it is not influenced by colour perception, which as previously stated varies between individuals as colour thresholds reduce with increasing age. Although this has the ability to enhance an expert's ability to assess a bruise, it cannot account for any non-visual factors which could influence blood coagulation and/or healing times. Therefore, the levels of bilirubin you would expect to see would vary but not be accounted for by this analysis technique.

Tracking bilirubin levels could be useful in understanding a bruise timeline, yet their modelling of the skin is not accurate enough. Although it contains the three layers of the skin, it does not take into consideration the effects of blood travelling through the tissue. Therefore, the study's representation of what happens during bruise formation and healing is incorrect. This drawback is acknowledged by the authors of this investigation.

Furthermore, their method becomes impractical within a forensic context. This is due to the difficulties surrounding taking continuous measurements over a period of time after a claim of physical assault or abuse.

5.2.3 Tracking of Bruise RGB Values

Grossman et al (2011) aimed to objectify bruising visual analysis. Their study involved employing a vacuum pump to produce bruises on volunteers and then took colour photographs under standard conditions daily until the bruise was no longer visible. They then used Photoshop to standardize the photographs and measure the red, green and blue (RGB) values, tracking their levels and ratios to each other during the bruise timeline.

Unfortunately their results were not very successful, with the only correlation between bruises being visible in the comparison of two bruises located on the same person.

However, there is potential for this method of analysis to be improved as it was found to be reproducible. The main concern was with their standardization technique. Although standardization is important, this study employed both set photography conditions and digital standardization. This caused some of the photographs to become either under or over exposed and thus unable to be used, with the other images being over-manipulated.

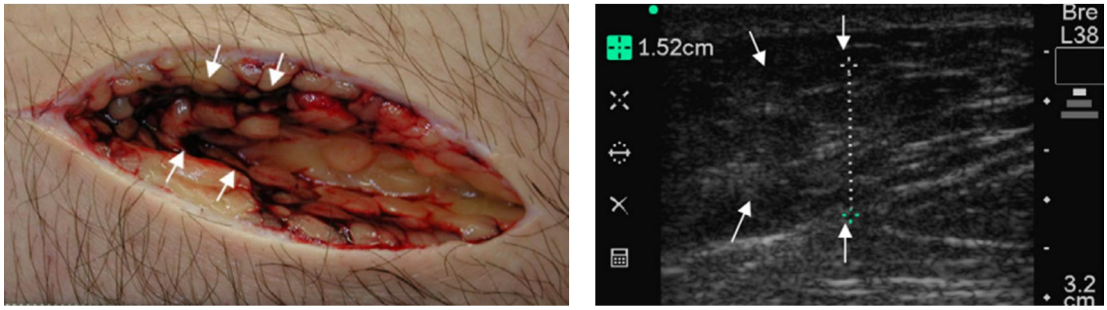
The method of bruise replication used within this investigation is not ideal as it does not represent how bruises are formed as a result of blunt force trauma. If this method could be replicated, with a more realistic method of bruise formation and more appropriate photography standardization, the measurement of RGB ratios has the potential to be valuable in the evaluation of bruising characteristics and bruise age.

5.2.4 Depth of Bruising Determined Using Ultrasound

Another method used to attempt characterisation of bruises was through the use of ultrasound imaging. A study by Mimasaka, Oshima and Ohtani (2012) investigated using ultrasound to measure depth and thickness of 10 bruises in forensic autopsy

cases, then comparing the results with macroscopic investigation. They also used the ultrasound analysis on 16 bruises present on 8 volunteer children.

They found a good correlation between using ultrasound and the measurements obtained during autopsy (Figure 5.2) and that this technique could be used on living volunteers (Figure 5.3). They were also able to show that the thickness of a bruise decreases over time and that this has an effect on the colouring of the bruise.



a. **b.**

Figure 5.2: *Ultrasound Imaging of Bruising on Autopsy – a. Macroscopic Findings, White Arrows Indicate Location of Subcutaneous Haemorrhage b. Ultrasound Image of Bruise, White Arrows Indicate Area and Depth of Bruising* (Mimasaka, Oshima and Ohtani 2012)

However, although this is a potential method for non-invasive, accurate evaluation of bruise depth and thickness, the study does highlight the difficulties in interpreting the image. A trained sonographer is required to ensure that the instrument is used correctly and the images are interpreted correctly, thus measurement errors cannot be eliminated.

Furthermore, it is unknown what effect ultrasound has on bruise shape. On application, it may cause the pooled blood to disperse giving a false representation of its true shape. Therefore, any deduction on the force which would have been responsible to form the bruise after ultrasound recordings have been taken would be inaccurate.

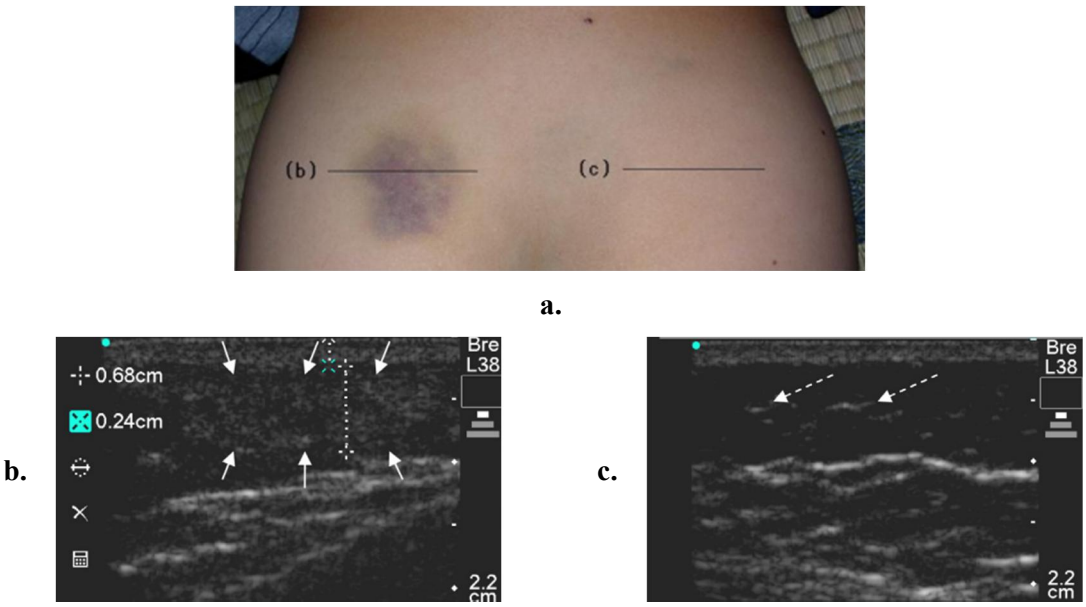


Figure 5.3: *Ultrasound Imaging of Bruising on a Living Volunteer – a. Colour Image of Bruise (b) and Control Area (c) b. Ultrasound of Bruised Area, White Area Indicating Area AND Depth of Bruising c. Ultrasound of Control Area, White Arrows IndicateArea of No Bruising and Location of the Fibrous Partition Within the Skin* (Adapted from Mimasaka, Oshima and Ohtani 2012)

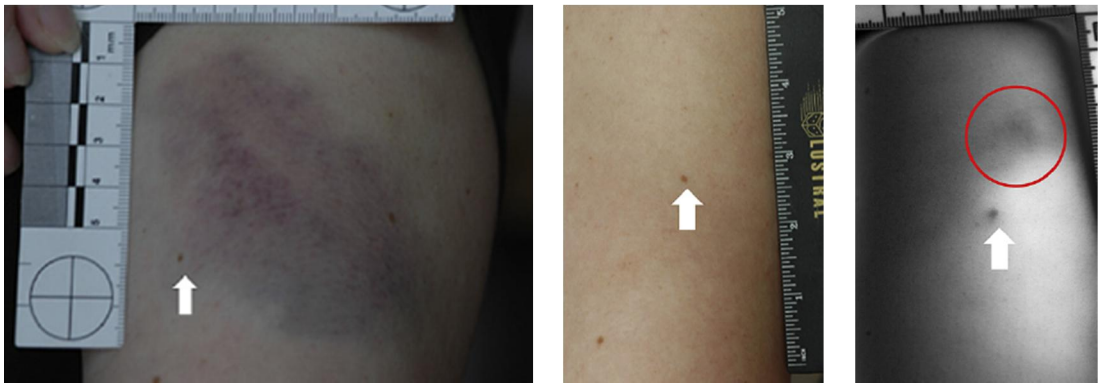
5.2.5 IR Photography to Visualise Non-Visible Bruising

A more successful attempt to improve the visual analysis of a bruise involved the use of IR photography to identify sites of bruising when the bruise itself is no longer visible to the naked eye.

Rowan et al (2010) located bruising on 10 adult volunteers and the photographs were taken using natural sunlight for illumination. Out of all the bruises they photographed, only one was still visible using IR imaging when no longer visible to the naked eye (Figure 5.4). Although they obtained only one positive result, their findings highlight the potential for the use of alternative photography.

Their lack of positive results may be due to their opportunistic method of photography, as it was not possible for them to arrange image collection at regular times. Their lighting conditions also could have influenced their ability to observe positive results. Their study was carried out between the months of November and April, between 10 am and late afternoon. This inevitably means that their photography conditions were never constant for all volunteers and the authors report

that on the day of obtaining their positive result, there was significantly more bright sunlight in comparison to other days.



a. **b.** **c.**

Figure 5.4: *Positive Result for Identifying a Bruise Using IR Photography (White Arrow Indicates the Mole Used as a Location Marker) –* a. *Original Appearance of Bruise b. Image Showing Bruise Has Fully Healed to the Naked Eye c. Bruising Visible Using IR Camera, Indicated by Red Circle* (Adapted from Rowan et al. 2010)

The potential for investigating the non-visible characteristics associated with bruise development, their visualisation after appearing fully healed to the naked eye and their relationship with the size of impact force could be possible.

5.2.6 Ageing a Bruise Using Visible Light Photography

This article written by Stam, Holst and Buczek (2012) looked at developing a camera system which used the colour distributions present to determine the age of a bruise. Their measurement system consisted of a camera with a filter which only allowed specific wavelengths of visible light (between 440 nm and 700 nm) through. The bruised area of skin was illuminated with a ring of cyan, blue and white coloured LED lights and the recording apparatus (the camera) would adjust to maintain a high sensitivity. Some of this light is absorbed by the tissue, the rest reflected. This amount of reflected light differs with the varying levels of haemoglobin and bilirubin present within a bruise. Specifically, haemoglobin absorbs light at wavelengths of 430 nm, 540 nm and 575 nm and bilirubin absorbs light at 470 nm. During recording, a total of 131 images are taken, each image taken over a narrow 2 nm wavelength. This produces a 3D record showing the varying light intensities for each point on the skin surface and for each of the different wavelengths used.

From using this equipment it has been reported that young bruises (about 24 hours old) can have the time of impact determined to within 30 minutes of the true time. Bruises of 5 or more days old have been reported to be aged within 16 hours of impact.

This article addresses the time taken for the images to be collected, stating that the 90 seconds required is too long. However, it is stated that if the results can be confirmed within the first few images, then fewer recordings are required, thus significantly speeding up the process. However, although a promising method acknowledged as requiring further research, it is unknown what, if any, influential factors were taken into consideration when determining the age of the bruises (e.g. person's age, impact force etc.).

5.2.7 Mechanical Parameters of Bruise Formation

The mechanical parameters of subcutaneous bruise formation have rarely been investigated. A study by Desmoulin and Anderson (2011) involved a single participant (caucasian male in good health), being subject to 12 mass impacts (six at 1.9 kg and six at 2.6 kg), at various locations on their lower legs.

Using a force plate and potentiometer, a force profile for each impact was produced. The impact forces ranged from 342 N to 874 N and by using this information, the mechanical parameters including pressure, tissue stiffness and absorbed energy could be inferred. Furthermore, any relationship between the parameters and bruise formation could be determined.

They found that where the tissue was stiffest, there was a greater chance of bruise formation. This stiffness was influenced by the density of the underlying subcutaneous tissues and the extent of vascularity in the area of impact. However, although useful, their data only relates to one individual. Therefore their findings cannot be stated as true for the population as a whole. This type of investigation has the potential to be expanded upon, through use of a larger selection of volunteers and testing on various limbs to confirm or refute their findings.

6 Pilot Study

6.1 Aim

Using a custom built apparatus, the aim of the pilot study was to determine the appropriate drop heights and impactor mass criteria for the main study. These parameters were based on the previous study by Desmoulin and Anderson (2011), where the minimum pressure required to initiate bruise formation on one person's lower leg is 1720 kPa.

This study was carried out on the study investigators, after Ethical Approval had been granted by the University of Strathclyde's University Ethics Committee. The Ethics Form submitted is shown in Appendix 1.

6.2 Materials

6.2.1 Impact Recording System

The equipment consisted of an impact apparatus (20 cm tall PVC pipe with internal diameter of 10.2 cm mounted over an arm rest), an impactor (2 cm x 5.8 cm aluminium curved-edge cylinder), 10g limit, pre-calibrated, MicroStrain® G-Link® Wireless Accelerometer Node and a 2.7 kg mild steel mass. Single channel (vertical) accelerometer data was recorded at 1024 Hz.

The design drawings are shown in Appendix 2 and images of the components of the built rig are shown in Appendix 3.

6.3 Method

6.3.1 Method Modifications

The pilot study was originally designed to use drop heights of 11 cm and 17 cm. These heights were selected, as numerical estimations suggested that they will maintain accelerations below 10g (i.e. 98.1 m/s^2), the limit of the accelerometer. In these calculations, impact times of 0.04 seconds and 0.05 seconds were assumed, verified by a preliminary (pre-pilot) test on the chief investigator. The drop height

calculations are shown in Appendix 4 and the calculations determining which masses should be piloted is shown in Appendix 5.

However, on assembly of the apparatus it was decided that such heights may be too excessive, in terms of applied pain for this study. Therefore it was decided that drop heights of a few centimetres were to be investigated.

In the original plan, masses ranging from 3 kg to 5 kg were to be used. However, on assembly of the apparatus, masses greater than 3 kg were deemed to be too excessive for this study.

6.3.2 Method Used

The pilot study was conducted by the investigators of this study. A 2.7 kg mass was dropped onto the impactor from the heights of 3 cm, 4 cm and 5 cm. The impactor was positioned so that it did not extend out of the base of the apparatus and would lie flush against the skin of the forearm beneath it.

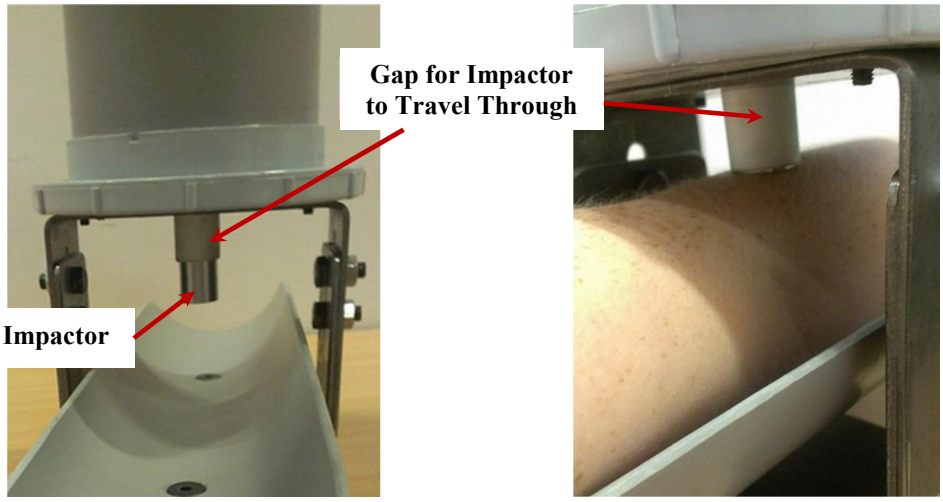


Figure 6.1: *Positioning of the Impactor on the Forearm – a. Guidance Tube with Enclosed Base and Area for Impactor to Travel Through Once Impacted b. Impactor Resting on the Forearm Without Extending Further Than the Base of the Apparatus*

6.3.3 Results

By varying the drop height, bruises were formed as a result. Between investigators, the degree of bruising visualised varied indicating that varying degrees of injury occurred as a result of the consistent impact conditions.

During testing, it was found that having the weight resting on the arm felt more painful than the impact itself. Consequently, it was decided to test resting a 4.8 kg mass upon the impactor onto the skin for up to 60 seconds, instead of impacting it. The rationale for this is that this type of loading mimicked a grab hold, rather than a blunt force impact, the analysis of which is of equal importance in Forensic Science. The dead weight loading was also found to initiate bruising in a similar method as how finger pad bruising is formed in cases where an individual has been physically restrained. Therefore, it was decided to incorporate this method of bruise initiation into the main study.

7 Main Study Methodology

7.1 Aim

Using the impact time, drop height and impactor mass criteria determined from the pilot study, the aim of the main study was to initiate bruise formation on volunteers. After the initial impacts, daily photographs were taken using colour, IR and UV imaging. Using all acquired data, a force profile was generated for each impact. The changes in RGB values were also tracked over bruise development and healing, along with an investigation into whether any non-visible characteristics of bruising could be detected.

7.2 Ethics and Volunteers

Ethical approval for this study was obtained from the University of Strathclyde's University Ethics Committee. All recorded data was pseudo-anonymised for use in this study.

The Participant Information Sheet and Consent Form are shown in Appendix 6 and Appendix 7 respectively.

The study was performed on 5 volunteers (1 male and 4 female) between the ages of 18 and 45 years. The exclusion criteria for the study were:

- Those who suffer from haemophilia, alcoholism, heart disease, cancer, chronic lower respiratory disease (e.g. asthma or emphysema), Alzheimer's disease, diabetes, nephritis (inflammation of the kidney) or have suffered a stroke.
- Those at a higher risk of blood clot formation, i.e. if considered medically obese (BMI > 30), medically underweight (BMI < 19), pregnant, a smoker or have a family history of inherited clotting disorders.
- Those who have suffered a musculoskeletal pathology trauma to the forearms, or have deformity of the arms.
- Currently on any medication or drug (prescribed or non-prescribed).
- Currently taking aspirin.

- Currently taking any herbal remedies or dietary supplements, e.g. ginko biloba.
- Presence of identifying marks, tattoos and/or piercings on forearms
- No alcohol intake 24 hours prior to study.

7.3 Impact Production

7.3.1 Method

The participants were asked to put an arm of their choice through a wooden partition and rest it in the arm rest. This screen was put in place to conceal the experimental apparatus from view and to ensure that the participant was unaware of the exact moment of impact. Therefore, the participant was able to remain as relaxed as possible, unable to tense up their muscles in anticipation of impact. As in the pilot study, the impactor was positioned so that it did not extend out of the base of the apparatus and would lie flush against the skin of the forearm beneath it.

Using the predetermined parameters, the 2.7 kg mass was dropped from the heights of 3 cm, 4 cm and 5 cm. The mass was dropped on the posterior forearm, between the proximal and medial areas, with the accelerations of each mass being recorded by the accelerometer.

The accelerometer was attached to the top of the 2.7 kg mass while the mass was lifted and dropped by using string. The string was marked at 1 cm intervals to indicate drop height (Figure 7.1) when in line with the top of the apparatus.

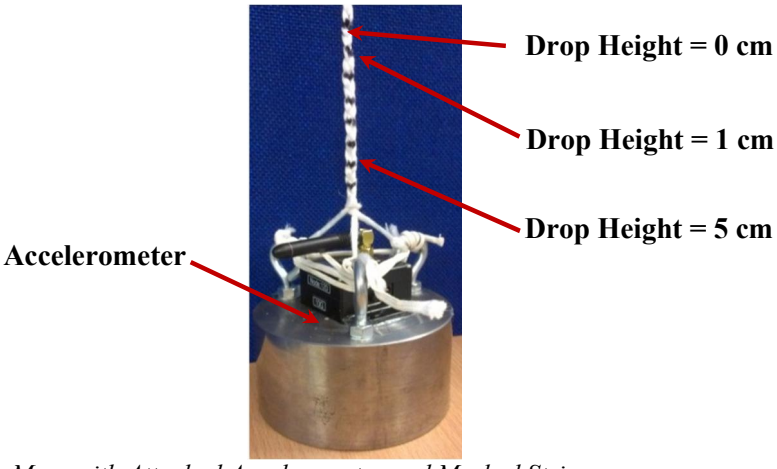


Figure 7.1: *2.7 kg Mass with Attached Accelerometer and Marked String*

Before each impact, the forearm was photographed using colour, IR and UV imaging to produce control images. Photographs of the impact area were then taken 2 hours after each impact occurred and then at 24 hour intervals after the time of impact until no longer visible.

7.3.2 Force Profile Generation

The vertical acceleration data was recorded via data logging at 1024 Hz, using the Node Commander® Software.

The data was then viewed and manipulated through Microsoft Excel to generate a force profile and thus determine the characteristics of each impact, taking into consideration that the mass was under free fall conditions.

7.3.2.1 Force Profile

From the acceleration values obtained, a force profile was derived by the equation:

$$F = m \times (a - g),$$

where F is the force, m is the mass dropped, a is the recorded acceleration and g is the acceleration due to gravity (-9.81 m/s^2). Once this profile had been generated, the data was cropped. The initial point of interest was identified as the minimum force recorded, corresponding to the initiation of freefall. This was close to zero, however, friction forces within the guide tube meant that 0 N was never actually achieved. Analysis was stopped at peak force.

7.3.2.2 Peak Pressure

Using the peak impact force and the area of impact (i.e. the surface area of the impactor in contact with the forearm), the peak pressure (P.P.), also known as peak stress, was calculated using the equation:

$$P.P = \frac{Peak\ Impact\ Force}{Area\ of\ Impact}$$

7.3.2.3 Impact Velocity and Displacement

As velocity can be defined as the integral of acceleration with respect to time, a standard trapezoidal numerical integration scheme was used to determine impact

velocity. This same scheme was then applied to the velocity data to determine the impact displacement (defined as the integral of velocity with respect to time).

The equations (derived from each integration), used to generate both the velocity and displacement profiles are shown below.

$$V = (\bar{a} \times \Delta T) + V_x,$$

where V is the velocity, $\bar{a}$ is the average acceleration, ΔT is the change in time and V_x is the velocity at the previous time point.

$$D = \bar{V} \times \Delta T + D_x \ ,$$

where D is the displacement (in millimetres), $\bar{V}$ is the average velocity, ΔT is the change in time and D_x is the displacement at the previous time point.

7.3.2.4 Work Done

Work done is defined as the integral of force with respect to distance. As above, a standard trapezoidal integration scheme was applied to calculate the work done by the falling mass. The derived equation used is shown below.

$$W = \bar{F} \times \Delta D + W_x \ ,$$

where $\bar{F}$ is the average force, ΔD is the change in displacement (in meters) and W_x is the work done at the previous time point.

7.3.2.5 Impulse of the Force

The energy impulse is defined as the change in momentum (i.e. change in amount of motion of the falling mass) and was derived using the standard trapezoidal integration scheme, with the derived equation used being shown below.

$$I = \bar{F} \times \Delta T + I_x \ ,$$

where $\bar{F}$ is the average force, ΔT is the change in time and I_x is the impulse at the previous time point.

7.3.2.6 Tissue Stiffness

Tissue stiffness is defined as the tissue's resistance to deformation when subject to set loading conditions. However as the skin response is time dependent, by producing a plot of force against displacement the rate of change of the applied force, an overall indication of tissue stiffness can be provided. It should be noted that this only refers to the skin's response to a compressive impacting force and not forces applied in any other direction.

7.4 Finger Pad Bruise Simulation

The contralateral forearm to that used during the impact test was rested on the arm rest as before, with the impactor resting on the volunteer. The 4.8 kg mass was then lowered onto the impactor and left for 15 seconds before being removed. The volunteer was then asked to move their forearm so that the procedure could be repeated for 30 and 60 seconds at a different locations. Photographs were also taken before and after the procedure, then daily as was done for the bruises produced from the impacts. As the mass and area of contact were constant, the applied pressure was 1.5 kPa.

7.5 Photography

Both colour, reflective IR and reflective UV imaging was carried out daily for the duration of the study. Lighting conditions remained constant each time using artificial light (i.e. not sunlight), with camera settings being set individually for each photograph, minimising the risk of under and/or over exposure. As much as possible, photographs were taken at approximately the same time the impact force was applied on the initial day of the study, thus generating a sequential visual representation of the development and healing of the bruise.

7.5.1 Camera Imaging

An 18 megapixel Canon EOS 600D camera with 50 mm lens was mounted on a height adjustable lighting stage. This lighting provided the artificial light required for

the colour imaging. Each image was of the forearm, between the elbow and the wrist. The aperture and camera height setting used are shown in Table 7.1.

For IR imaging, a Mason Vactron Quaser 40 was used to produce IR lighting conditions within a dark room. A green/yellow excitation filter with a range of 503-591 nm was used. This blocked UV light from being transmitted. The camera was fitted with a filter which only allowed light of wavelengths greater than 720 nm to pass through. This therefore allowed for observations and photographs to be taken within the range of IR light. Positive results were recorded when IR absorption within the bruised areas was observed.

Colour Imaging		**IR Imaging**	
Aperture	F 1.8	Aperture	F 5.0
Camera Height	46 cm	Camera Height	46 cm
Filter	N/A	Filter	720 nm

Table 7.1: *Aperture and Camera Height Parameters Used Throughout the Study*

7.5.2 VSC Imaging

A Foster & Freeman VSC 40/HD with a 2 megapixel camera was used to generate UV images of the forearms. These images were compared to those obtained from using the camera imaging. Furthermore, the UV illumination of the arm was combined with red, green and blue filters to see how this affected the visibility of a bruise. The wavelength of UV light used was 365 nm as this is safe for exposure to human skin. Positive results were recorded when UV absorption was observed.

7.5.3 Image Manipulation

To standardise the images a colour calibration was carried out. A Gretag Macbeth Colour Checker was photographed and an AcrCalibrator script obtained from Chromoholics was run through Photoshop to calibrate the colour chart (The methodology of use and application was also obtained from Chromoholics). These

calibration settings were then saved and later applied to each of the images being standardised. These settings were only valid for the camera used within this study.

The elliptical marquee tool was used to select the area where the impactor had struck. If a bruise was formed and the size of the visible mark increased, the selected area was increased to include the whole bruise. This was to ensure that the changes in RGB values represented the bruise as a whole, not just its centre. The RGB values were obtained from the 'Histogram' section of Photoshop.

8 Impact Characteristics Results and Discussion

8.1 Force Profile of Impact

8.1.1 Development of Impact

For all impacts, there was a consistent pattern in the development of impacting force until its maximum load was reached. An example of this is shown in Figure 8.1.

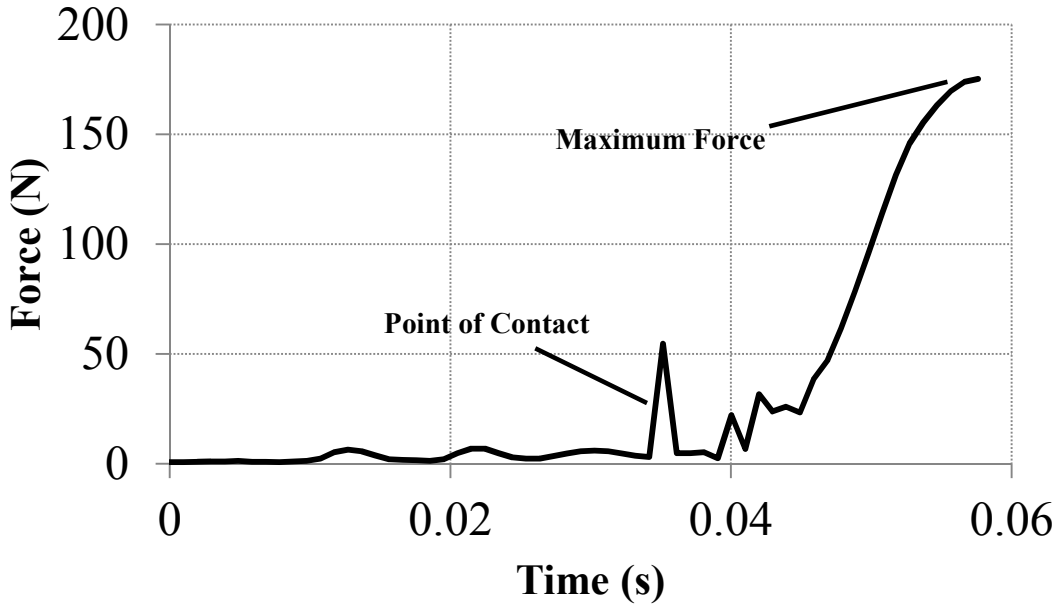


Figure 8.1: *Typical Impact Force Trace Observed – From the Point of Release Until Maximum Impact Force is Reached*

The first peak observed was present on all impact force traces obtained and was identified as the force due to the transient strike of the mass on the impactor. Since the impactor was resting on the skin, this point was defined as the start of the contact phase. After this peak, there is a steady increase up to the maximum force which is applied to the forearm, typically taking between 2 and 4 hundredths of a second.

The traces obtained for applied pressure follow the same pattern as the force traces mentioned above, as it is obtained by dividing by the constant contact area. From the point of release the pressure remains at approximately zero before producing a peak as the falling mass comes into contact with the impactor. After this, there is again a steady increase in the applied pressure until a peak level is reached (Figure 8.2).

For both the force and pressure traces the initial readings from the point of release until the first point of contact is not consistently zero, as would be expected (i.e. when in free fall no force is acting against the falling mass to keep it suspended in the air). This is likely due to interactions with the side of the guide tube, in that some minor frictional forces may have been produced as the mass came in contact with the sides of the tube. Hence the production of slight increases in force as the mass is released and falls. Another possible explanation is that the accelerometer calibration was not accurate.

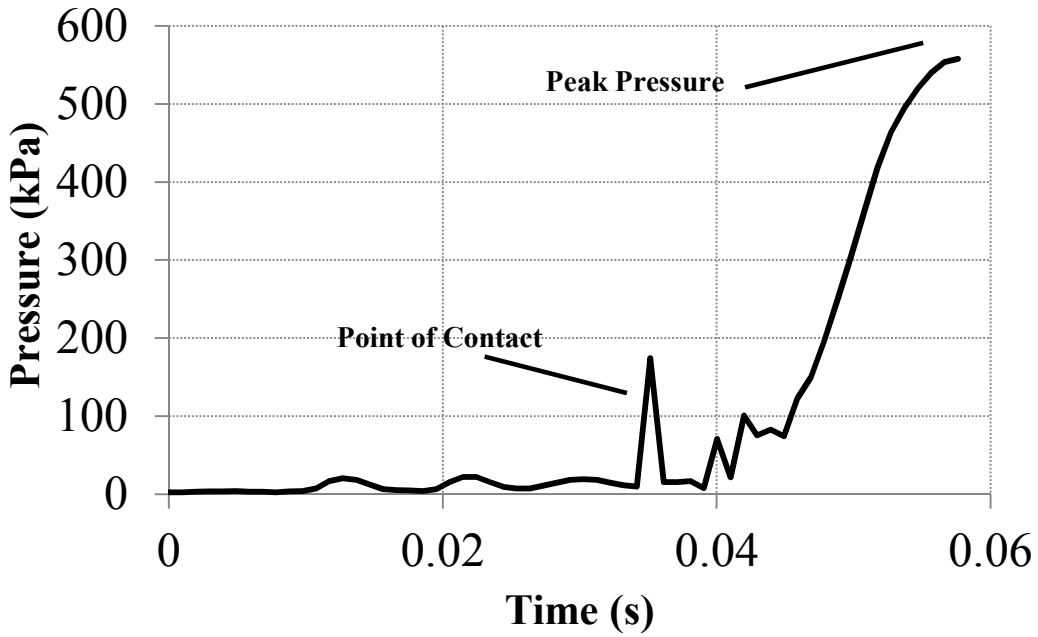


Figure 8.2: *Typical Impact Pressure Trace Observed – From the Point of Release Until Peak Pressure is Reached*

The traces obtained for the acceleration change again follows the same pattern as the traces mentioned before (Figure 8.3). From the point of release, the acceleration is at approximately -10 m/s^2. This is expected as the only force acting on the falling mass is gravity (-9.81 m/s^2), and any slight deviation from this value is likely due to a minor error in the accelerometer calibration.

At the point of initial contact between the falling mass and the impactor, the peak represents a sudden deceleration. As the impactor moves downwards onto the forearm, there is a steady increase in deceleration rate from approximately -10 m/s^2

to the maximum deceleration recorded. At this maximum deceleration, the mass and impactor have reached the point where the skin and underlying tissues of the forearm prevent them from traveling any further downwards.

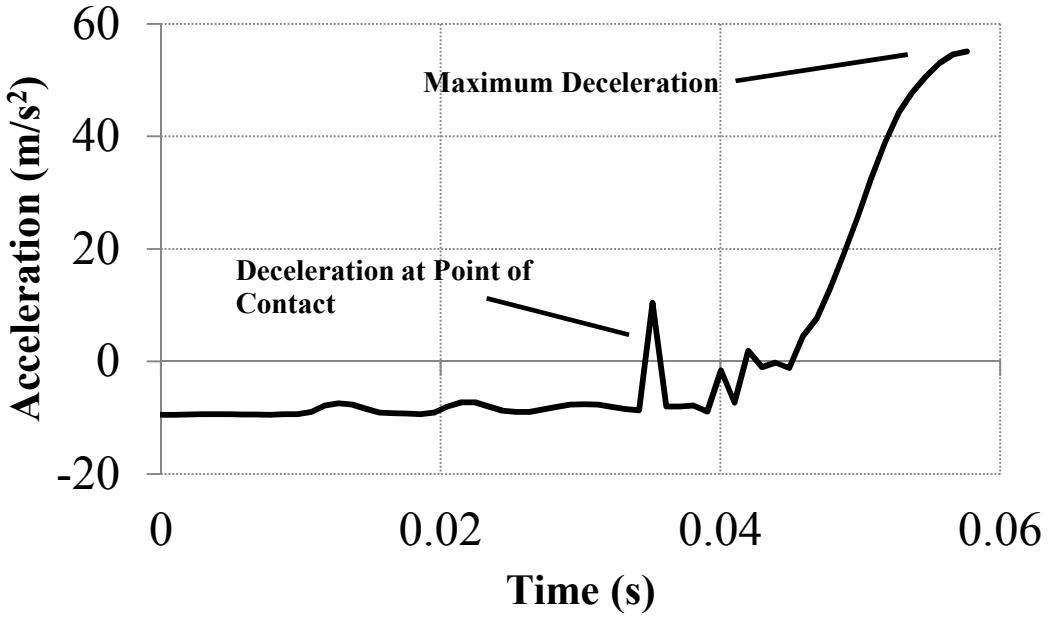


Figure 8.3: *Typical Acceleration Trace Observed – From the Point of Release Until the Point of Maximum Deceleration is Reached*

The typical velocity trace observed reflects the acceleration traces as is expected (Figure 8.4). As the mass falls with a constant acceleration, the velocity steadily increases in the downard direction (hence the negative values).

At the point of impact, the is a slight decrease in velocity. After this point, for approximately 0.01 seconds, the velocity continues to increase as the impactor moves freely downwards into the forearm. As the skin's collagen fibres align and thus begin to act against the impacting force, the velocity reaches a peak, before decreasing as the impactor begins to slow and ultimately cease moving down into the forearm.

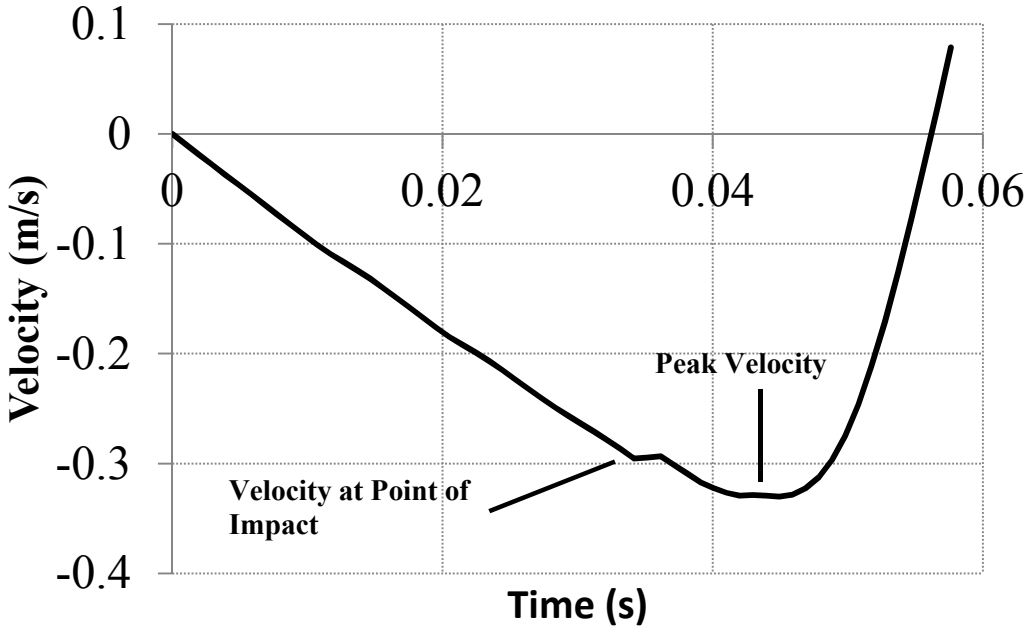


Figure 8.4: *Typical Velocity Trace Observed – From the Point of Release to the Point of Minimum Velocity*

The displacement curves observed for each impact followed the pattern showed in Figure 8.5.

After the point of contact (approximately 0.04 seconds), the level of displacement reflects the depth at which the impactor is able to travel downwards into the forearm. In this particular example, skin displacement reached -7.66 mm at the point where maximum force was reached.

All impact results and resultant graphs for each participant can be found within Appendix 8.

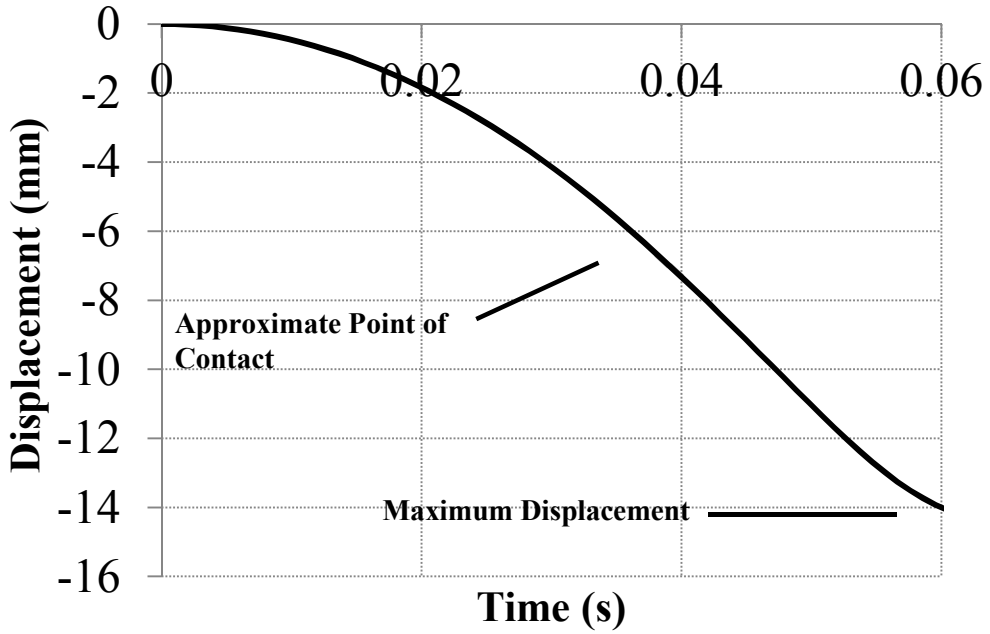


Figure 8.5: *Typical Displacement Trace Observed –From the Point of Release Until Point of Maximum Displacement*

8.1.2 Impact Characteristics

8.1.2.1 Observations

Comparing the 5 cm and 4 cm drop height (Table 8.1 and Table 8.2 respectively), there is an expected drop in the average impacting force, pressure, impact time and skin displacement as the drop height is decreased. The average values calculated from the data collected from the 3 cm drop height (Table 8.3), are higher than expected as they are higher than those obtained from the 4 cm impact. This could be due to several reasons, including the inaccuracies in maintaining a consistent drop height and varying anatomical locations of impact (See Section 10.1). It should be noted that the data for participant E were not successfully recorded for the 3 cm drop height. Therefore, no calculations could be carried out.

Across all three drop heights, the difference between each participant's results appears to show significant variation. For example, for a 5 cm drop height the skin displacement ranged from -2.37 mm to -13.66 mm, a difference of -11.29 mm. The standard deviation for this impact (4.15 mm) emphasised this variation between

participants. If each individual had the same muscular tone to their forearm, a smaller standard deviation would be expected. However, this was not the case thus the large variation observed. As above, these findings would also have been influenced by the inaccuracies within the method of bruise initiation.

	Max Force (N)	**Peak Pressure (kPa)**	**Time to Max Force from Contact (s)**	**Skin Displacement (mm)**
A	175.21	557.72	0.045	-5.87
B	201.70	642.02	0.055	-13.66
C	265.67	845.66	0.041	-5.84
D	234.28	745.73	0.031	-2.37
E	190.09	605.08	0.051	-7.66
Average	213.39	679.24	0.045	-7.08
SD	36.42	115.94	0.01	4.15

Table 8.1: *Impact Characteristics for a 5 cm Drop Height*

Furthermore, in cases where the locations of impact were able to be kept constant between participants, discrepancies would result due to variations in the physical structure of the forearm. The muscle and fat content between participants varied and this influences the skins response to a sudden impact.

	Max Force (N)	Peak Pressure (kPa)	Time to Max Force from Contact (s)	Skin Displacement (mm)
A	141.59	450.69	0.061	-7.00
B	177.74	565.77	0.061	-3.09
C	193.81	616.92	0.049	-5.97
D	163.16	519.36	0.053	-7.77
E	231.01	735.31	0.035	-4.70
Average	181.46	577.61	0.052	-5.71
SD	36.42	95.98	0.01	1.66

Table 8.2: *Impact Characteristics for a 4 cm Drop Height*

In response to a higher impact, the average skin displacement is higher than that observed for the lower impact forces. This is due to the skins response to impact and therefore, the rate at which the collagen fibres of the skin are able to align with the applied force. For lower forces, the fibres are able to reorganise at a faster rate to resist the applied force. As impacting force increases a larger quantity of collagen fibres within the skin are required to act against the force, hence taking longer to align. This results in the skin having a greater deformation. In both cases the deformation acts to protect the skin as it causes the impact force to be displaced across the surface of the affected limb, reducing any detrimental effects it could have, for example a bone fracture (Burkhart, Schinkel-Ivy and Andrews 2013).

	Max Force (N)	Peak Pressure (kPa)	Time to Max Force from Contact (s)	Skin Displacement (mm)
A	177.59	565.29	0.057	-8.63
B	216.72	689.85	0.037	-5.36
C	164.95	525.04	0.031	-2.55
D	219.85	699.79	0.039	-7.12
E	-	-	-	-
Average	194.78	619.99	0.041	-5.92
SD	23.95	76.25	0.01	2.26

Table 8.3: *Impact Characteristics for a 3 cm Drop Height*

8.1.2.2 Statistical Analysis

Statistical analysis was performed using a one-way ANOVA (Analysis of Variance) test on Microsoft Excel. This showed that the apparent difference between impact characteristics and varying drop height was not significant.

For each characteristic, ANOVA was performed using a 0.05 (5%) level of significance, i.e. if the *p*-value obtained was less than 0.05, there would be a significant level of variance.

Taking maximum force as an example (data shown in Table 8.4), the null and alternative hypothesis were taken as:

H_0: There is no difference between the maximum forces produced as drop height is varied.

H_a: There is a difference between the maximum forces produced as drop height is varied.

	Drop Height		
	5 cm	**4 cm**	**3cm**
Peak Force	175.21	141.59	177.59
	201.70	177.74	216.72
	265.67	193.81	164.95
	234.28	163.16	219.85
	190.09	231.01	-
Average	213.39	181.46	194.78
SD	36.42	30.15	23.95

Table 8.4: *Dataset for Varying Drop Height and Peak Force used in ANOVA Analysis*

The *p*-value was calculated to be 0.348, thus as $p > 0.05$, H_0 is accepted and H_a rejected.

Therefore, there is no significant difference between maximum forces as drop height is varied.

A summary of the *p*-values calculated for each impact characteristic is shown below in Table 8.5.

Impact Characteristic	***p*-Value**
Maximum Force	0.348
Peak Pressure	0.348
Time to Maximum Force From Contact	0.313
Skin Displacement	0.756

Table 8.5: *p-Values Obtained for Each Impact Characteristic*

The fact that statistically, no significant difference is observed as drop height changes implies that there must be other factors influencing the results. For example, tissue stiffness would alter the degree of skin displacement and thus impact time. Furthermore, the inconsistencies in drop height would also affect the results obtained.

Full ANOVA results for each impact characteristic is shown in Appendix 9.

8.1.3 Tissue Stiffness

To gain an idea of tissue stiffness during a blunt impact, a plot of force against displacement was produced with the gradient of the linear region being determined. For example, for participant A, the rate of change was found to be approximately 73.78 N/mm per second. However, no trace provided a completely linear gradient which could be accurately interpreted (Figure 8.6).

Looking at Figure 8.6, it can be seen that in all cases the tissue response as time progresses follows the same pattern. Generally, for the lower impacting forces which were produced a gentler gradient was observed. This implies that the level of impacting force determines the degree of skin deformation.

This can be explained through the collagen fibre rearrangement within the skin during impact. For lower impacts, the rate at which the fibres act to resist the force is lower, thus inferring that by allowing the skin to be more deformable, the forces and pressures applied can be absorbed and also transmitted away from the impact site.

For higher impact forces the gradients, although not significantly different, are steeper. This is due to the skin having a more immediate response to resist the impacting force and thus protect the underlying tissues of the forearm.

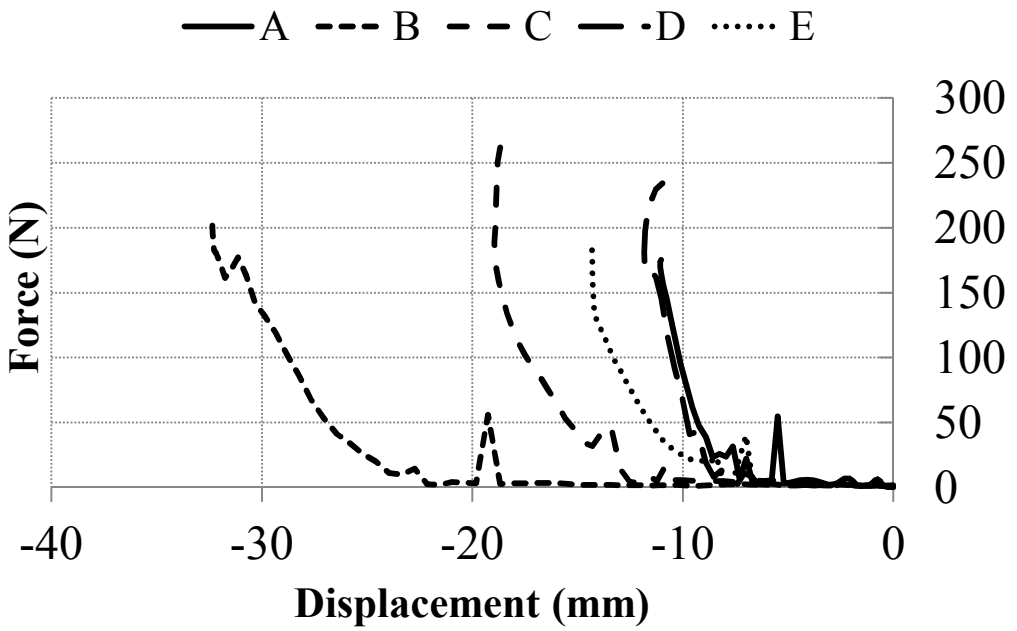


Figure 8.6: *Plots of Force Against Displacement for all Participants – 5 cm Drop Height*

8.1.4 Work Done and Impulse

8.1.4.1 Work Done and Statistical Analysis

It would be expected the level of work done would increase as impacting force increases. However, from looking at the work done values obtained from the recorded data (Table 8.6), it is difficult to identify a specific trend. This is most likely down to the varying tissue stiffness and impacting area inter- and intra-person. Thus, a one-way ANOVA test (with a 0.05 level of significance), was performed to determine if there was any significant difference between the results observed.

The *p*-value was calculated to be 0.66, and as this is greater than 0.05, the alternative hypothesis was rejected and the null hypothesis accepted.

Thus, there is no significant difference between the work done as drop height was varied. However, as previously shown there was no significant difference between impact forces or skin displacements as drop height was altered. Thus, this finding would be expected.

	Work Done (J)		
	5 cm	**4 cm**	**3 cm**
A	-292.44	-432.30	-240.27
B	-28.99	-181.96	-543.93
C	-501.81	-398.52	-197.93
D	-313.13	-473.29	-564.69
E	-379.16	-450.15	-
Average	-303.12	-387.24	-386.71
SD	173.65	117.96	194.48

Table 8.6: *Work Done Values Calculated For Each drop Height*

8.1.4.2 Impulse of the Force and Statistical Analysis

As the drop height decreases, the impact force would decrease. Therefore, the force impulse would be expected to decrease also. Looking at the results observed (Table 8.7), it is again difficult to establish a trend, as the only difference in average impulse is for that produced in the 4 cm drop (it is higher than that for the other drop heights).

Again possible explanations include the anatomical variances inter- and intra-person. The inconsistent drop heights may have also been a factor. Therefore, a one-way ANOVA test (with a 0.05 level of significance), was performed to determine if there was any significant difference between the values as a result of varying drop height.

The *p*-value was found to be 0.24, and as this is greater than 0.05, the alternative hypothesis was rejected and the null hypothesis accepted.

	Impulse of Force (Ns)		
	5 cm	**4 cm**	**3 cm**
A	1.70	2.66	0.66
B	0.09	2.54	2.56
C	2.60	2.56	1.60
D	2.56	2.35	2.02
E	1.82	2.33	-
Average	1.75	2.49	1.71
SD	1.02	0.14	0.80

Table 8.7: *Impulse of Force Values Calculated For Each drop Height*

Therefore, it was statistically proven that there was no significant difference between the impulse of forces produced as the drop height was varied. As with work done, as the impulse calculation is reliant upon force and time, which have been previously shown to have no significant difference as drop height was changed, it is expected that there would be no significant difference between the results of this impact characteristic either.

8.2 Varying Loading Conditions and Bruise Formation

8.2.1 Altering Drop Height

Not all impact forces resulted in bruise formation. In general, all impacts from 5 cm did form a bruise and most 4 cm and 3 cm impacts also formed a bruise (Table 8.8). As the drop hight and thus impact force decreases, it would be expected that the tendency for bruise formation would reduce. However, it should be noted that for participants C and D, as the apparatus could not be lowered onto the forearm thus,

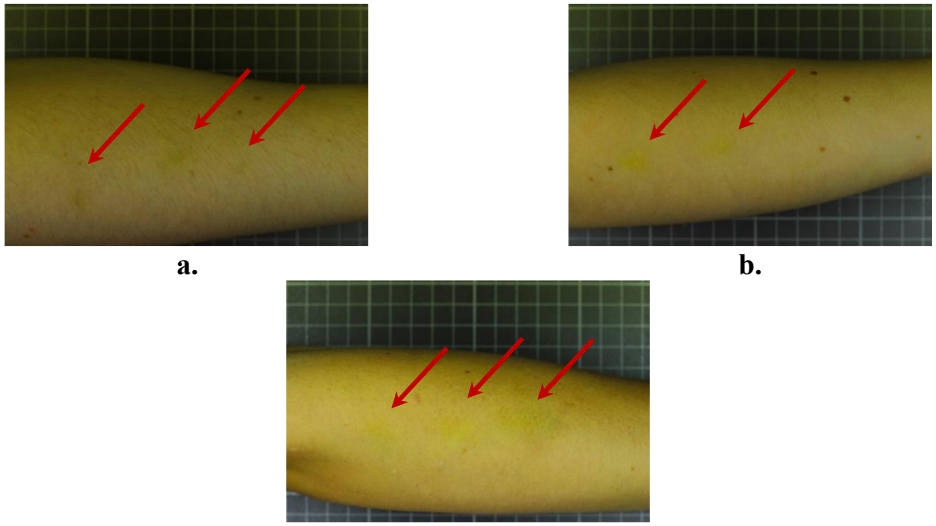
the 3 cm impacts were performed closer to the elbow than those for participants A, B and E.

This could therefore explain why all but one participant presented with a bruise after an impact from the lowest drop height. Furthermore, the lack of bruising on participant B may also be a result of being male. As previously stated males have less subcutaneous fat and thus participant B would not be expected to bruise as readily as the female participants.

	5 cm	**4 cm**	**3 cm**
A	1	1	1
B	1	1	0
C	1	0	1
D	1	0	1
E	1	1	1

Table 8.8: *Impacts Which Did and Did Not Initiate Bruise Development – 1 = Bruise was Formed 0 = No Bruise was Formed*

For all participants, where clear bruising could be visualised, the extent of bruising differed. This is likely due to the anatomical location on the forearm and along with the variations on muscle tone and subcutaneous tissue between participants. Looking at Figure 8.7, image c. shows the most extensive bruising. For image b., the impact order differed from the others (i.e. from left to right the impacts went 3 cm, 5 cm and 4 cm). In this case, the impact from a drop height of 4 cm had not produced a clear bruise by 5 days after impact. In comparison, for image a. the largest of the three bruises was for the impact from a drop height of 4 cm.



a. **b.** **c.**

Figure 8.7: *Varying Degrees of Bruising Between Participants – a. 3 Bruises, 6 Days After Impact b. 2 Bruises, 6 Days After Impact c. 3 Bruises, 5 Days After Impact*

8.2.2 Application of Constant Pressure

The application of a constant pressure (1.5 kPa) for varying lengths of time either produced little or no bruising (Table 8.9). Furthermore, as bruising was not as extensive, healing was more rapid than for bruising which resulted from an impact.

It is likely that the lack of bruising is due to the pressure alone not being enough to rupture the underlying blood vessels, and that an impact is required.

	60 s	**30 s**	**15 s**
A	0	1	0
B	0	0	0
C	0	0	0
D	0	0	0
E	0	0	0

Table 8.9: *Constant Pressures Which Did and Did Not Initiate Bruise Development – 1 = Bruise was Formed 0 = No Bruise was Formed*

9 Bruise Imaging Results and Discussion

9.1 Two Hours After Impact

Overall, there was no apparent evidence of bruising visible to the naked eye. In all cases, the red mark left by the impact from a 5 cm drop height was still visible after 2 hours (Figure 9.1).

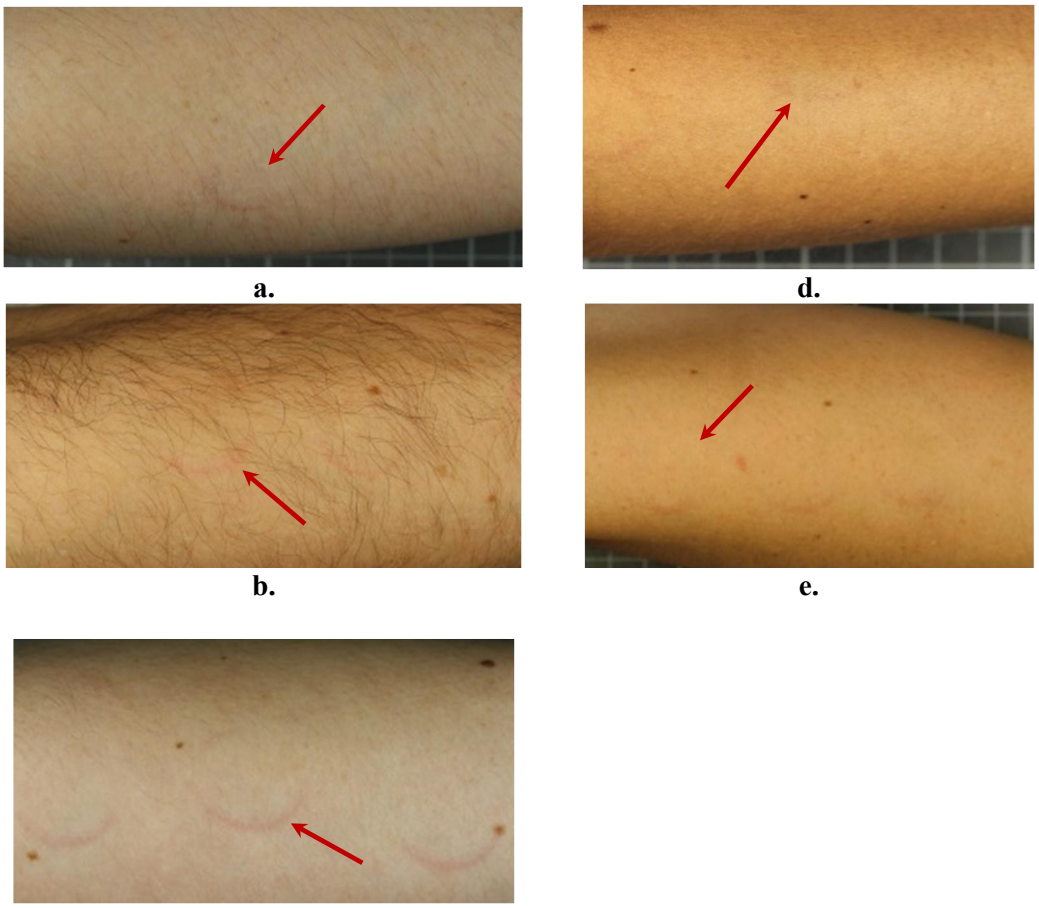


Figure 9.1: *Red Mark from Highest Impact Still Visible After Two Hours – Indicated by Red Arrow (Unstandardized Images)*

Three individuals still showed the marks left from all 3 impacts (Figure 9.2), however the degree of visibility varied between individuals. This could be a result of differences in gender and thus the levels of subcutaneous fat within the forearm, or level of fitness, as this can also influences the muscle-fat ratio within the body.

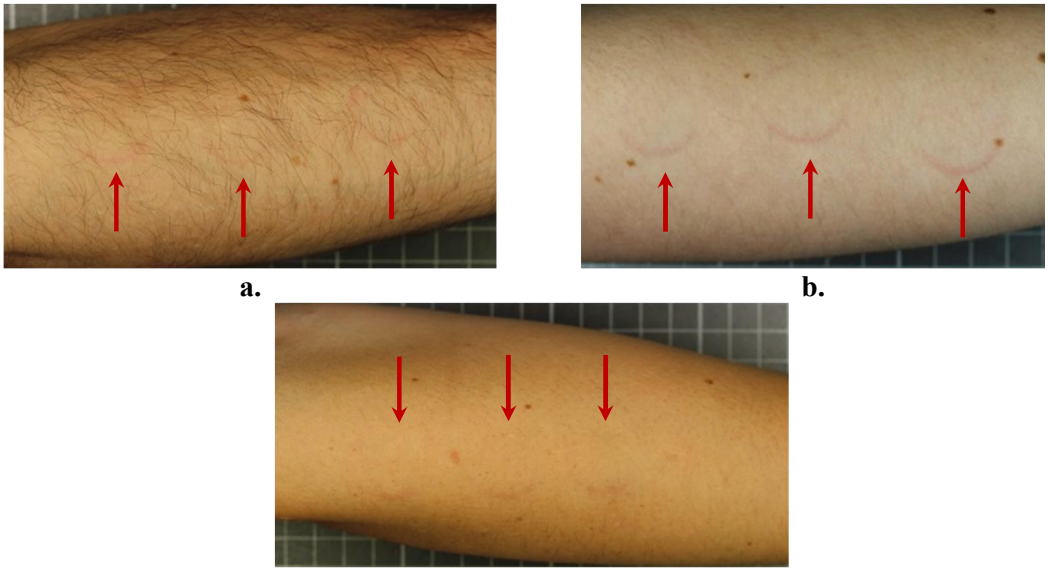


Figure 9.2: *Participants Where Mark Produced By All Three Impacts Are Still Visible After Two Hours – Indicated By Red Arrows*

9.2 Daily Colour Imaging

9.2.1 Observations

No bruise showed any distinct red, blue or purple colourations which would be expected within the first few days of development. In some cases no bruise was visible at all. This was most likely due to the applied force being too low to cause significant vessel rupture and blood release. As a result, the bruises produced appeared more green and yellow once visible. This implies that as the level of released blood was low, the body is able to breakdown the haemoglobin at a faster rate than that which would be observed in more severe bruising injuries.

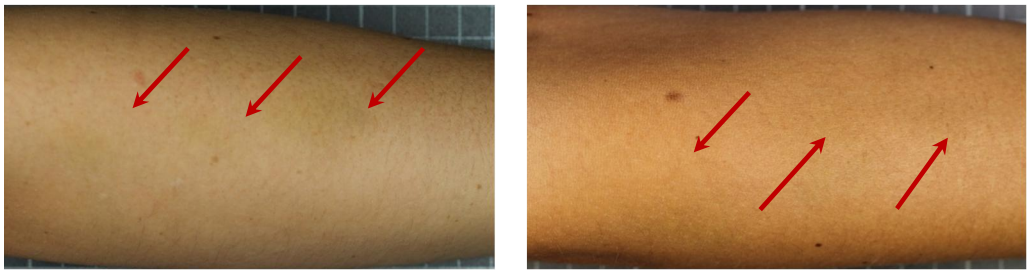
Overall, the changes in impact force did not influence the degree of bruising observed. In many cases, where bruises had formed, the most extensive observed resulted from the 3 cm drop height. This may be explained through the anatomical location of the impacts and how their structure varied between participants.

The time taken for bruising to fully heal was approximately 12 to 13 days for the female participants and 8 days for the male volunteer (who presented with no more than a red mark in the areas of impact). This difference in gender and tendency to

bruise was found to support previous findings that females are more likely to bruise. This is due to their greater subcutaneous fat layer.

The use of colour imaging was found to be good in the documentation and tracking of bruising over their development and healing, particularly in comparison to the standardised images where the change in colour results in all bruising to appear yellow (i.e. the changes in tone of green and yellow are lost to the naked eye).

However, skin colour did reduce visibility of bruising (Figure 9.3). Within the visible light region, melanin (the pigment within the skin which is responsible for skin colour), is largely responsible for light absorbance. (Lister, Wright and Chappell 2012). Therefore, for the identification of bruising, the standardised images provide greater definition as the effects of light absorbance are reduced, i.e. the skin does not appear as dark.



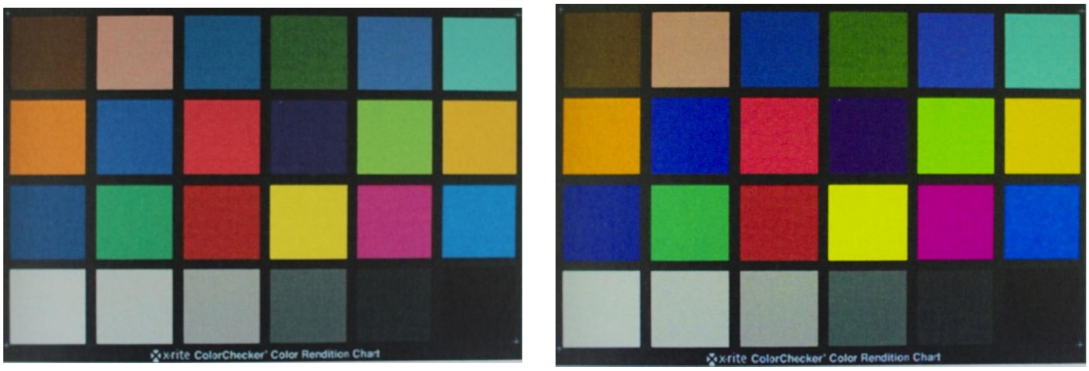
a. **b.**

Figure 9.3: *Influence of Skin Colour on Bruise Identification With the Naked Eye After 7 Days – a. Visible Bruising on Pale Skin b. Unclear Bruising on Tanned Skin*

9.2.2 RGB Value Tracking

9.2.2.1 Standardising of Images

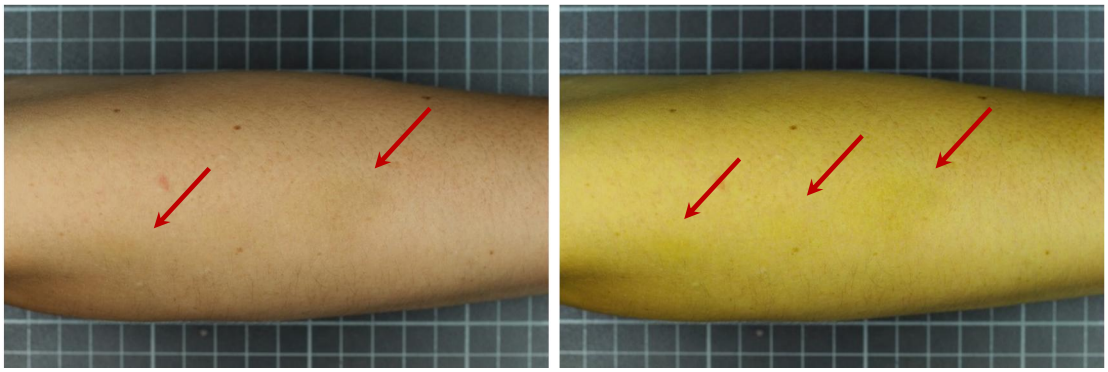
By standardising the colour chart (Figure 9.4), and applying the setting to the colour photographs, a true representation of what is detected by the camera was produced.



a. **b.**

Figure 9.4: *a. Pre-Calibration Image of Colour Chart b. Post-Calibration Colour Chart*

Along with ensuring that all images were under the same conditions, it also appeared to increase the contrast between skin and bruise, making them more visible (Figure 9.5).



a. **b.**

Figure 9.5: *Increased Contract from Standardising Images – a. Pre-Standardised Image (2 Clear Bruises) b. Post-Standardised Image (3 Clear Bruises)*

9.2.2.2 RGB Results

9.2.2.2.1 Impact Bruises

For each individual participant, the changes in RGB values observed followed the same general pattern for each of the three impacts (Figure 9.6). In all the results, the red and green values were much higher than the blue values observed. In some cases the blue values were recorded as zero and this is most likely due to the standardising method making the images appear more yellow in colour.

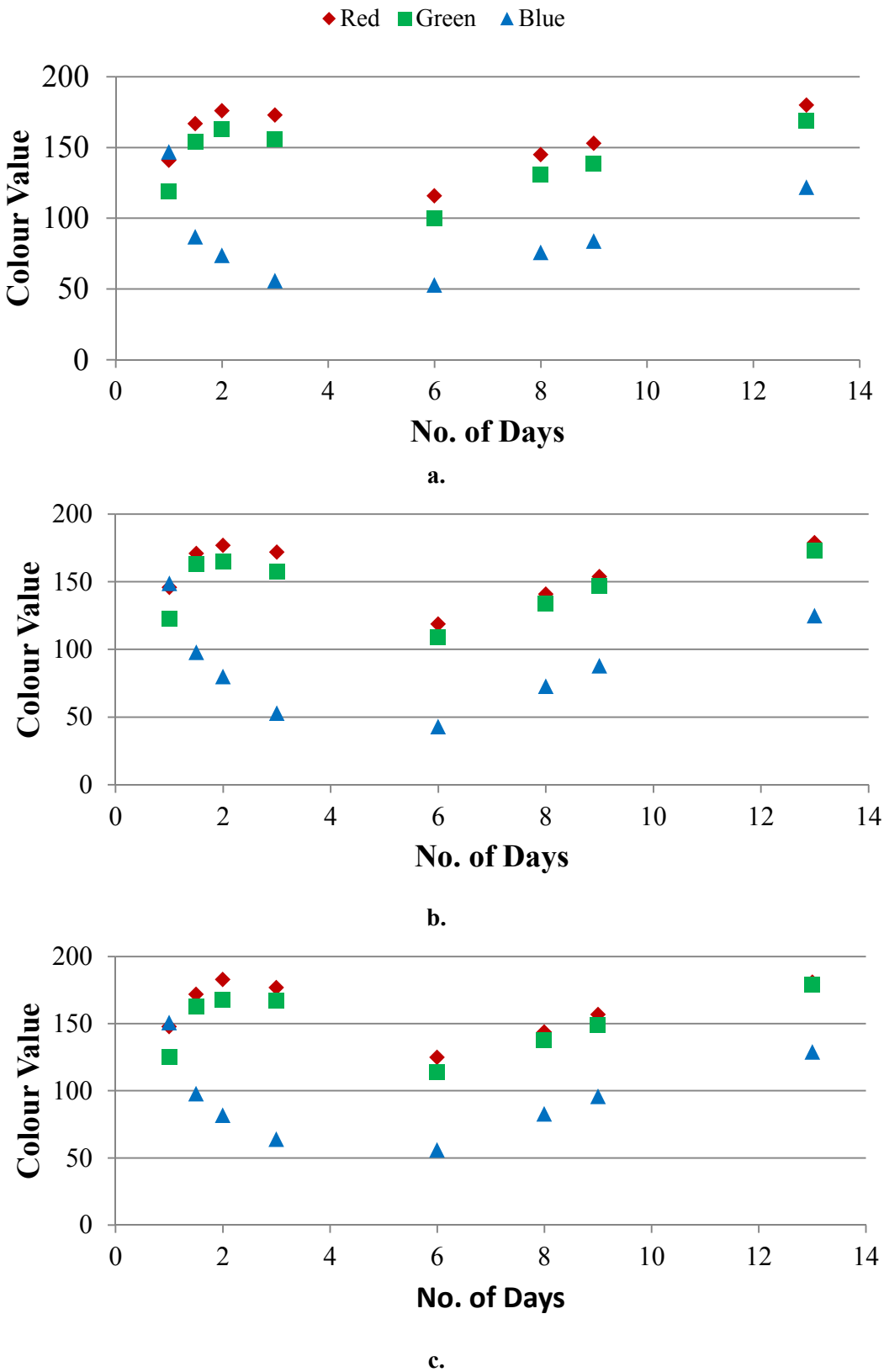


Figure 9.6: *Typical RGB Pattern for Bruising From Each Drop Height a. 5cm Drop Height b. 4 cm Drop Height c. 3 cm Drop Height*

The levels of each colour observed varied between people for each impact however, they remained fairly similar (e.g. reds were all observed above a level of 150). Although standardising may have affected the levels of blue recorded, the observations of blue tended to be lower for participants B, D and E, who appeared to have more tanned skin. It should be noted that where a bruise could not be visually identified in the picture, RGB measurements were still taken. They showed that there were still changes in colour over time at the impact sites, even though they could not be perceived by the naked eye.

The average RGB values for all participants for each impact, from 5 cm (Figure 9.7), 4 cm (Figure 9.8) and 3 cm (Figure 9.9), were taken and plotted to gain an indication of the colour changes over time.

In general, the changes in red and green observed were not what was expected. Over the initial days after impact, it would be expected that bruising would appear more red in colour. Then, as time goes on, the levels of red to fall and green to increase, as the haemoglobin is broken down. The levels of green would then be expected to fall as the bilirubin product is eliminated from the body.

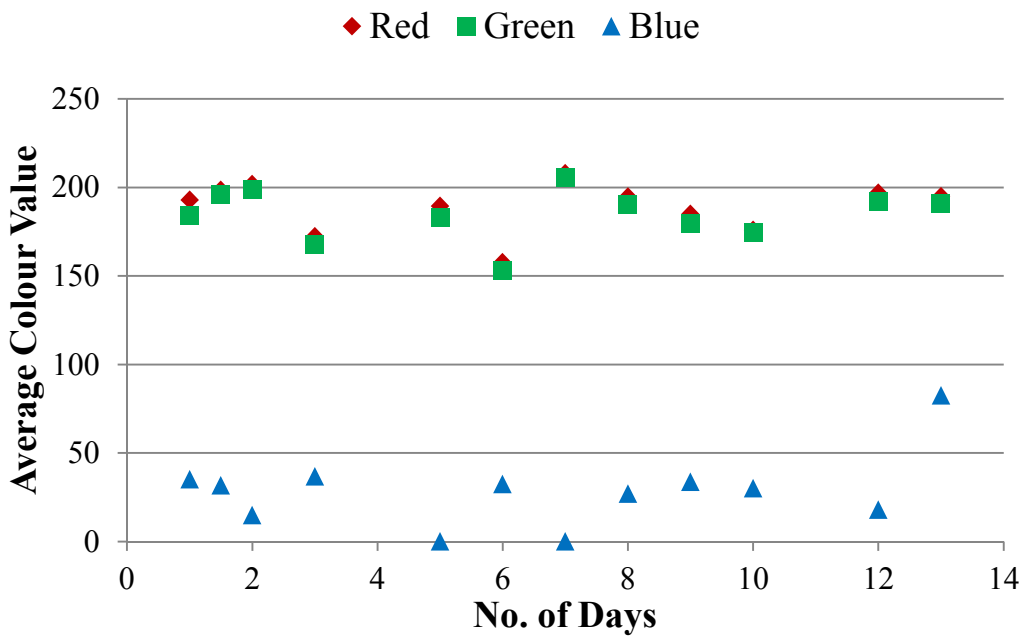


Figure 9.7: *Average RGB Values for A Bruise Resulting From a 5 cm Drop Height*

However, these graphs show that overall the level of red observed was fairly similar to the level of green. The average level of green observed does appear to increase after the first day, then decrease as would be expected after approximately day 7. However, between days 3 and 6 there appears to be a drop in both red and green values. This could be a result of the imaging not being possible for that day range after impact as it fell over a weekend where no imaging took place.

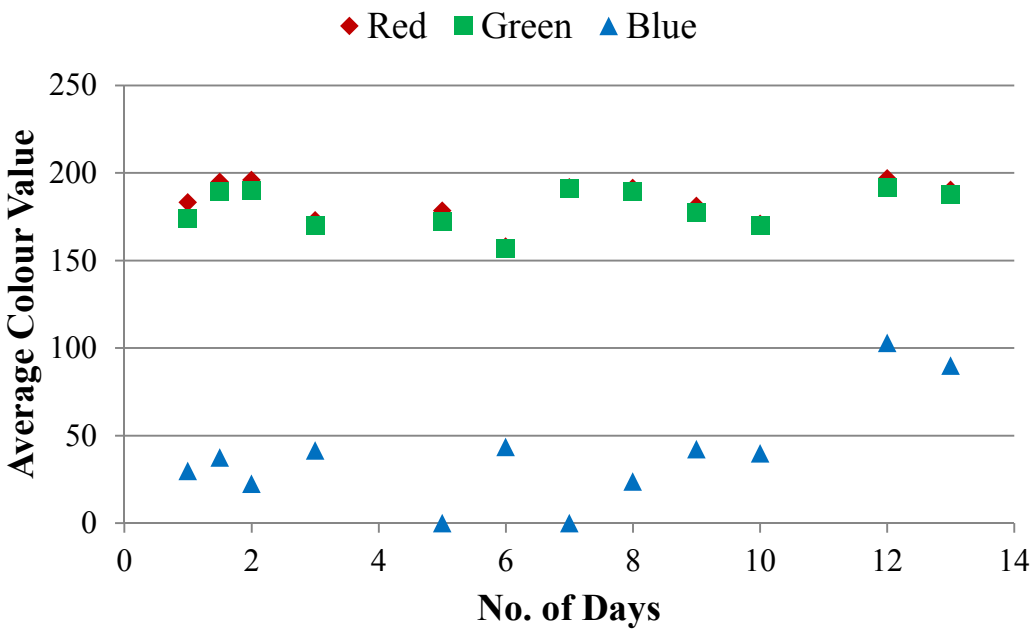


Figure 9.8: *Average RGB Values for a Bruise Resulting From a 4 cm Drop Height*

Comparing the average RGB values observed for each impact, they all have the same general pattern. As the mechanism of bruise development and healing is the same for all people and as no volunteer had any physical or medical condition which would interfere with the development and healing (as was required to participate), this was as expected.

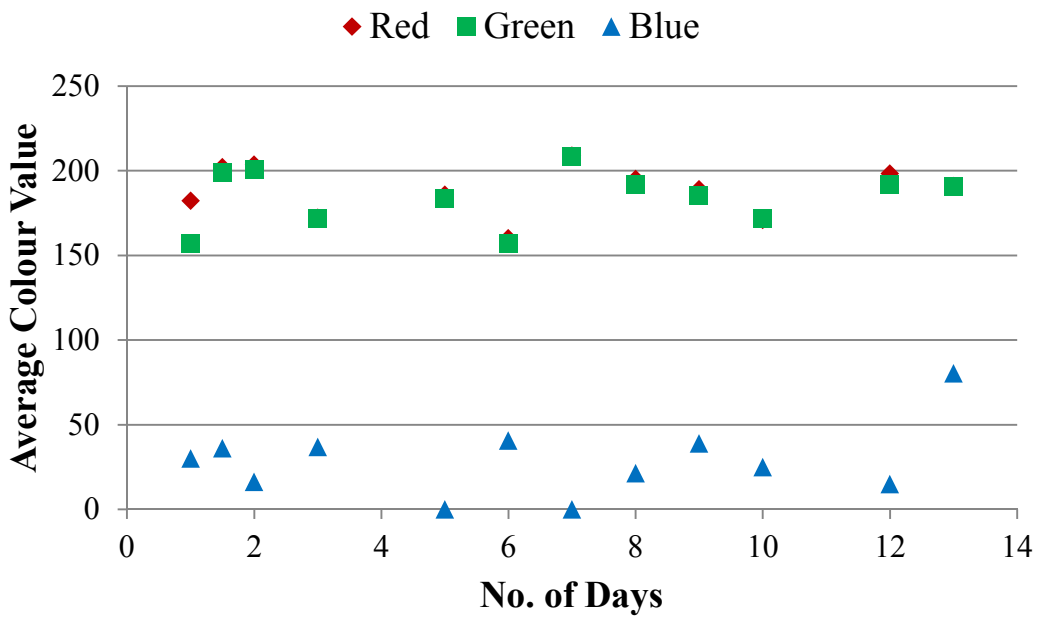


Figure 9.9: *Average RGB Values for a Bruise Resulting From a 3 cm Drop Height*

It would be expected that the levels of each colour observed would increase with increasing impact force however, this did not occur.

All recorded RGB data can be found in Appendix 10.

9.2.2.3 Statistical Analysis

As with the results of impact characteristics, ANOVA analysis was performed using a 0.05 (5%) level of significance, to determine the significance between the average RGB values obtained as drop height was varied.

Taking the red values recorded as an example (data shown in Table 9.1), the null and alternative hypothesis were taken as:

H_0: There is no difference in the red colour values recorded as drop height is varied.

H_a: There is a difference in the red colour values recorded as drop height is varied.

The p-value was calculated to be 0.615, thus as $p > 0.05$, H_0 is accepted and H_a rejected.

Therefore, there is no significant difference between the recorded red colour values as the drop height is varied.

This finding supports the previous statements of how the changes in colour appear consistent over the three drop heights. As this is not what was expected, i.e. the extent and thus colours present within bruises should vary with varying drop heights/impact forces etc., it implies that other experimental factors must have influenced the results For example, the inconsistent drop heights and anatomy variances, between participants and impact locations, of the forearm would affect the degree of bruising formed.

	Drop Height		
	5 cm	**4 cm**	**3 cm**
Red Values	193.0	183.4	182.4
	198.6	195.0	202.2
	201.8	196.2	203.8
	172.3	173.0	172.3
	189.5	178.5	186.0
	157.7	158.0	160.3
	208.0	192.0	209.0
	194.8	191.6	195.5
	185.0	181.3	189.3
	176.0	171.0	171.0
	197.0	197.0	198.5
	195.0	190.5	191.0

Table 9.1: *Dataset of Red Colour Values and Varying Drop Height Used in ANOVA Analysis*

Colour	*p*-Value
Red	0.615
Green	0.676
Blue	0.455

Table 9.2: *p-Values Obtained for Each Colour Value*

The conclusion of 'no significant difference' was determined for the green and blue values, and a summary of all *p*-values obtained is shown in Table 9.2.

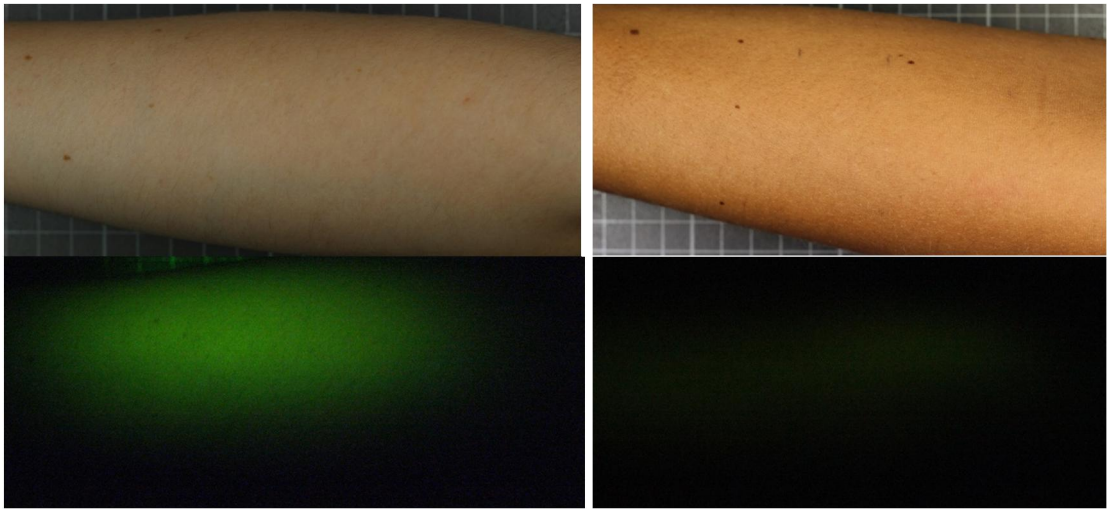
The full ANOVA results for all three colours are shown in Appendix 11.

9.2.2.4 Held Mass Bruises

Although to the naked eye some minor bruising was detected on some participants, it was very difficult to locate these bruises in the camera images (both pre- and post-calibrated). Therefore, due to a lack of usable images, no RGB values were obtained.

9.2.3 IR Imaging

During the photography process, when the images could be viewed on the digital camera's viewing screen, there was a possibility that some bruising could have been detected. However, on transferring the images onto the computer, the quality of the image decreased making all images appear darker than they did on the camera. Consequently, this change in image quality reduced the ability to identify bruising which is known to be there and also in identifying bruising after they are no longer visible to the naked eye. This applied for both the bruises formed by impact and by the application of a constant pressure.



a. **b.**

Figure 9.10: *Effect of Skin Colour on IR Reflectance – a. Pale Skin Providing Greater IR Reflectance b. Tanned Skin Providing Reduced IR Reflectance*

Skin colour appeared to influence the absorbance and reflectance of IR light. For skin which was more tanned, a greater level of IR light was absorbed by the forearm, resulting in darker images. In comparison, for paler skin the IR light was more readily reflected providing brighter images (Figure 9.10).

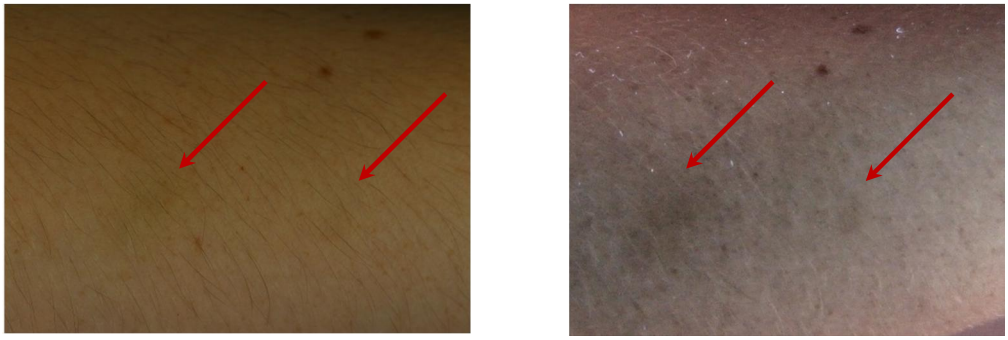
9.2.4 UV Imaging

9.2.4.1 UV Lighting

The use of UV lighting showed greater success in the identification of bruising. As with the IR imaging, it was not possible to identify any bruising on the forearm which had been subject varying constant pressures.

For all participants, the bruises formed as a result of an impact force were able to be detected using UV imaging. An example is shown below in Figure 9.11.

However, this appeared to be only once the bruises were developed enough to be identified with the naked eye. This therefore implied that UV imaging cannot be used to identify bruises in the early stages of its development. This cannot be confirmed as in all cases, bruising had gone from being not visible to fully developed over a weekend when no imaging occurred.



a. **b.**

Figure 9.11: *Positive Identification of Bruising Using UV Lighting Once Bruise Has Developed – a. Colour Image of Bruising After 6 Days b. UV Image of Bruising After 6 Days*

9.2.4.2 UV Lighting in Combination With Filters

The VSC allowed for filters to be applied while under UV conditions, revealing the images in their red, green and blue components. In all cases this affected the visibility of the bruises being observed.

The application of the red filter made the UV images appear lighter. Contrast between skin and bruise was reduced however, bruising could still be identified. The green filter made the images appear darker in comparison to the red component images. Contrast between skin and bruising was increased. The blue component filter produced the darkest images with the greatest contrast between bruising and skin.

As the bruising timeline progressed, the visibility of bruises decreased most rapidly when viewed using the red filter. As any red tones within a bruise are the first to disappear, this explains the shorter period of time which bruising was visible under these conditions.

The degree of contrast observed in the green component images increased as the red component contrast decreased. This relates to the decreasing red tones and increasing greens as the haemoglobin is broken down and converted to biliverdin. This contrast then decreases as the biliverdin is converted to yellow bilirubin and then removed from the impact area.

As the green tones develop and become darker as time progresses, the blue component shows increased contrast between bruising and skin. This contrast follows the observations made with the use of the green filter. Although the blue component would be expected to be most prominent at the earlier stages of bruise

development and healing, the clearer observations at later stages of bruise healing could be due to the depth of injury. Thus, as the broken down haemoglobin is removed, producing a faint bruise to the naked eye, the blood components deeper with in the tissue are revealed under this imaging technique. Alternatively, as the changes in bruise contrast follows the changes in contrast presented by the green component images, as the green tones become deeper, blue becomes prominent to reflect this. An example of all UV images recorded, showing the effects of the application of each filter is shown in Figure 9.12.

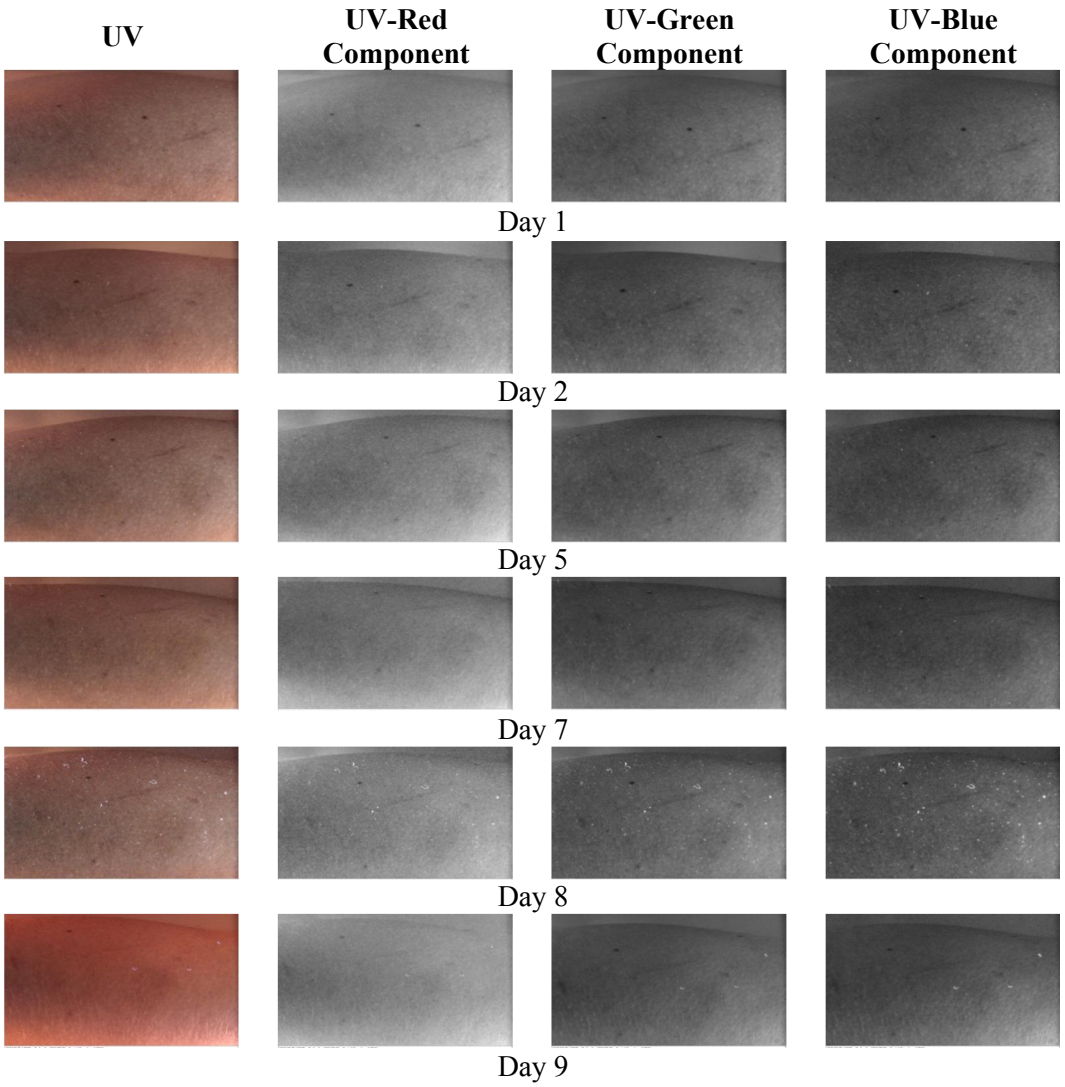


Figure 9.12: *Typical Timeline of UV Images Recorded*

As with colour and IR imaging, skin colour appeared to interfere with observations as results were not as clear on tanned skin. Healing times may also have influenced the images however, to the naked eye, both participants showed signs of bruising up until day 12 (Figure 9.13).

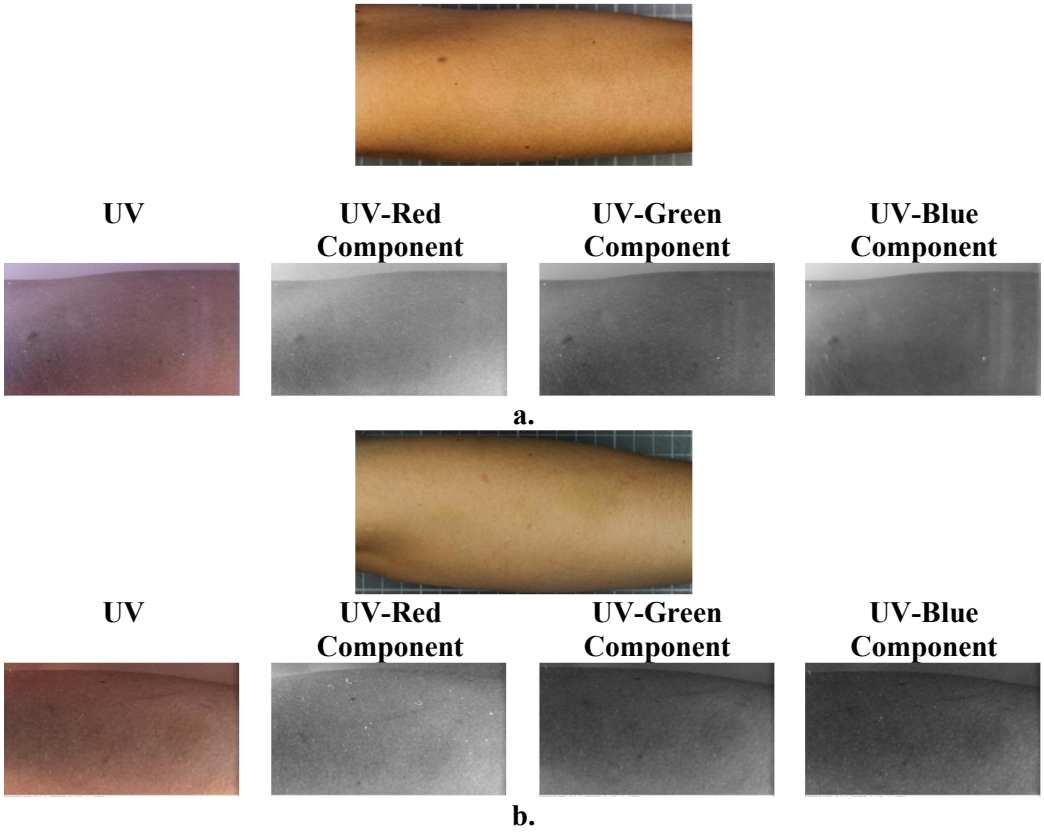


Figure 9.13: *Effect of Skin Colour and Identification of Bruising Under UV Lighting Conditions – a. Images Taken After 7 days on Tanned Skin b. Images Taken After 7 Days on Pale Skin*

9.3 Findings Compared to Those of Baker, Marsh and Quinones

A study published in 2013 by Baker, Marsh and Quinones investigated the use of various photography techniques in the documentation of concealed or faded bruises. They compared visible and cross-polarised white light, reflected IR and reflected UV lighting conditions and evaluated their use.

They found that the UV light was generally unsuccessful and that IR imaging did allow for some contrast when identifying bruises. They also determined that IR imaging showed greater potential for bruise enhancement on darker skin compared to

paler skin pigmentation. Both visible and cross-polarized white light provided the highest contrast images when identifying bruising, regardless of the skin colour being imaged.

Excluding cross-polarized light (as it was not used within this study), their findings on visible light photography are similar to what observed in this investigation. Colour photography had the least difficulties surrounding its use, provided contrast between skin and bruise for all skin types. It should be noted that skin colour did interfere with bruise observation.

Unlike Baker, Marsh and Quinones findings the IR images did not provide any positive results and was found to be significantly influenced by skin colour. This difference may be due to their method of IR imaging. They used a Quantum Flashgun to provide the IR light, thus the use of alternative sources in this study such as the Crime-Lite® manufactured by Foster + Freeman may have been more appropriate.

The results of UV imaging were more successful than those reported by the authors in 2013. Their method of producing the UV light source was through the use of the Quantum Flashgun. However, the use of this does not allow for specific control of the particular UV wavelength employed. This may be what resulted in the successful identification of bruising within this study, as a specific wavelength was able to be employed.

Note that all images obtained for all three methods of imaging and the standardised images are shown in Appendix 12.

10 Method Evaluation

10.1 Apparatus

10.1.1 Height Adjustment

The apparatus produced for bruise production was simple and easy to use. However, its design was not ideal. The guide tube had been fixed into place over the arm rest with the ability to be moved up and down to accommodate for the arm size of the participants. However, the guide tube was not able to be placed into an ideal position on some participants as it did not have the ability to be lowered far enough (Figure 10.1).

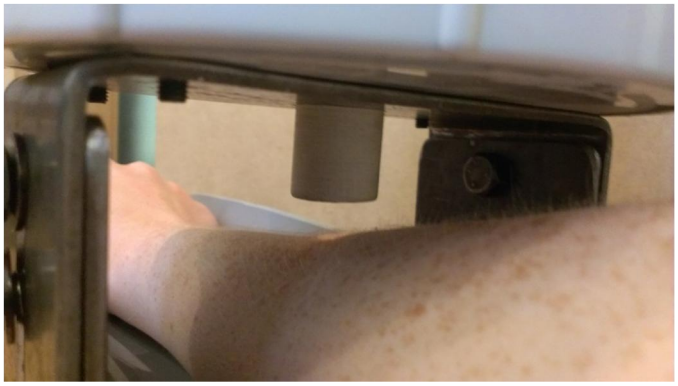


Figure 10.1: *Gap Between Apparatus and Forearm When the Hight is Adjusted to the Lowest Level*

As a consequence, several of the impacts had to be conducted fairly close to one another to allow the apparatus to lie flush against the skin. This may have influenced how the bruises formed over time and thus the shape and size of the bruises formed.

Furthermore, this resulted in some participants having impacts equally distributed down their forearm, while for others they were more localised at the proximal end of the forearm. Thus, anatomical location could also have influenced he production of a bruise. This is due to impacts nearer the elbow being over a more muscular area of the forearm where underlying blood vessels have greater protection from blunt force impacts. Furthermore, the gradient of the forearm from elbow to wrist produced from the underlying muscle, appeared to influence the extent of bruising formed.

10.1.2 Inaccurate Drop Height

The method of dropping the mass could also be improved. Although simple, the drop height cannot be guaranteed as consistent each time. This is confirmed through the drop heights calculated in this study (Table 10.1).

	5 cm	**4 cm**	**3 cm**
A	5.8	3.5	1.9
B	4.1	3.6	3.2
C	7.5	3.0	1.9
D	6.4	1.9	4.8
E	2.4	-	-
Average	5.24	3.00	2.95
SD	2.01	0.78	1.38

Table 10.1: *Recorded Drop Heights For Each Participant (Note For Participant E: Drop Height of 4 cm, Initial Contact Point Unclear So Drop Height Unable to be Determined – Drop Height of 3 cm, Data was not Successfully Recorded*

This table shows that although it was aimed to maintain consistent drop heights, the drop height employed could vary up to 2.5 cm. The average recorded drop heights for both the 4 cm and 3 cm were both lower than the target heights. The average drop height for the target 5 cm was greater than was aimed for. By looking at the standard deviation, the recorded drop heights for those supposed to be from 4 cm were closest to their target. The 5 cm drop height showed the greatest deviation, of approximately 2 cm.

Manually releasing the weight relied on a steady arm and personal judgment on when the marker on the string (which indicates drop height) is level with the top of the guide tube. The difficulties surrounding lifting and holding the mass from a level point also influences the accelerometer data. As only one person operated both

accelerometer recording and mass dropping, the accelerometer had to be recording before the mass could be held in place, thus making the initial reading appear noisy and the identification of the time point where the mass was dropped a little more difficult. Thus, a more automated release mechanism would be preferred as eliminates any inconsistences produced by dropping the mass manually.

These varying drop heights also influenced the impact characteristics observed. Plots were made of each impact characteristic against the calculated drop heights. With increasing drop height, it was shown that both maximum impacting force and peak pressure increased (Figure 10.2).However, the degree at which these characteristics increased was significantly different, as shown by the gradients of each trend line. For pressure, the gradient observed was 41.686, whereas for force, the gradient was much lower, at 10.687. Ideally, if the drop heights were able to be kept constant, this variance in results would not be observed.

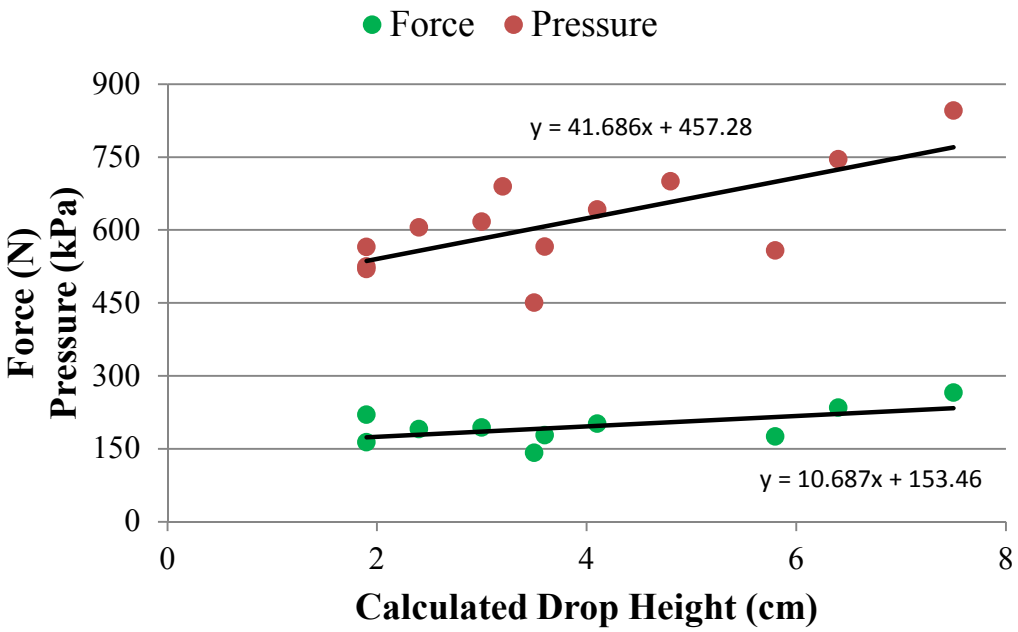


Figure 10.2: *Effect of Varying Drop Height on Peak Force and Peak Pressure*

Consequently, as would be expected, the level of skin displacement decreased with the increasing drop heights (Figure 10.3). It should be noted that there are some displacements which are much higher or lower than the general trend observed and that this is related to the tissue stiffness of each individual.

This varying skin displacement is linked to the trend observed between varying recorded drop heights and impact time (Figure 10.4). Impact time was shown to decrease as a result of the impact area becoming more resistant to the applied force, deflecting it away at a faster rate.

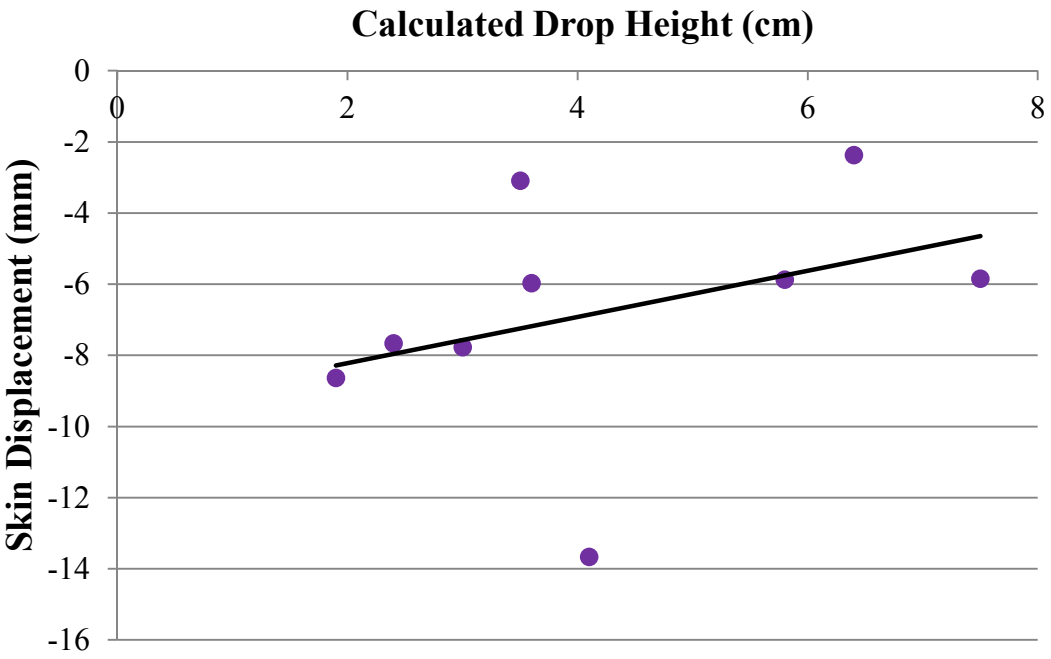


Figure 10.3: *Effect of Varying Drop Height on Skin Displacement*

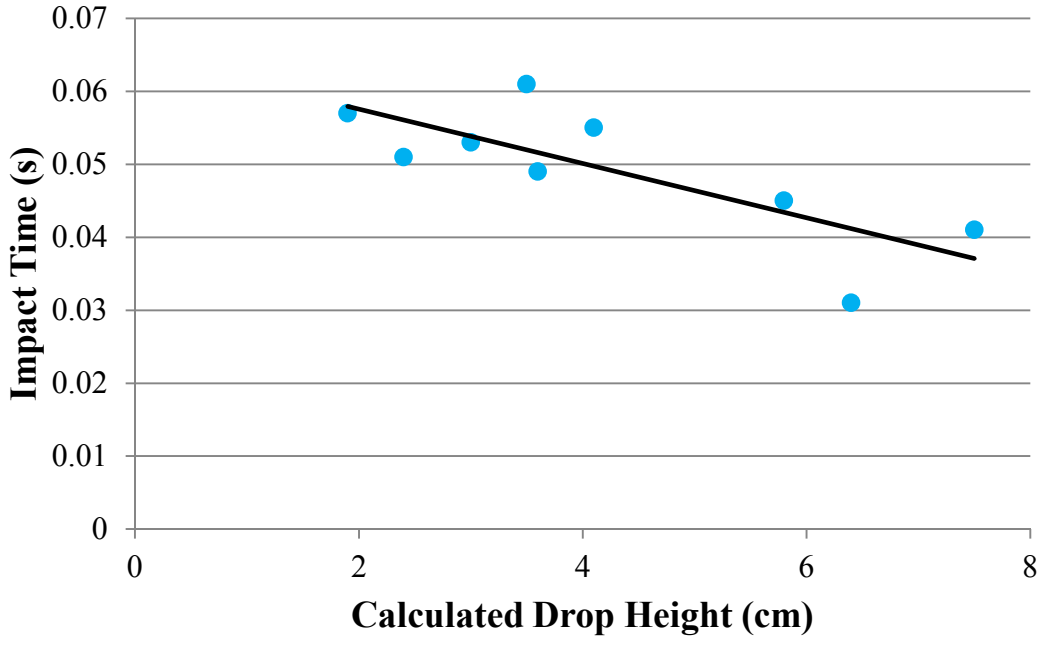


Figure 10.4: *Effect of Varying Drop Heights on Impact Time*

Furthermore, the work done and impulse of force characteristics were also affected by the inconsistent drop heights (Figure 10.5 and Figure 10.6 respectively). It was found that there was a general decrease in the work done and increase in impulse observed. However, unlike the other impact characteristics, the distribution of data points shows that the change in impact height does not have as significant effect, but factors such as tissue stiffness may be more influential.

Note all graphs and data used to produce them are shown in Appendix 13.

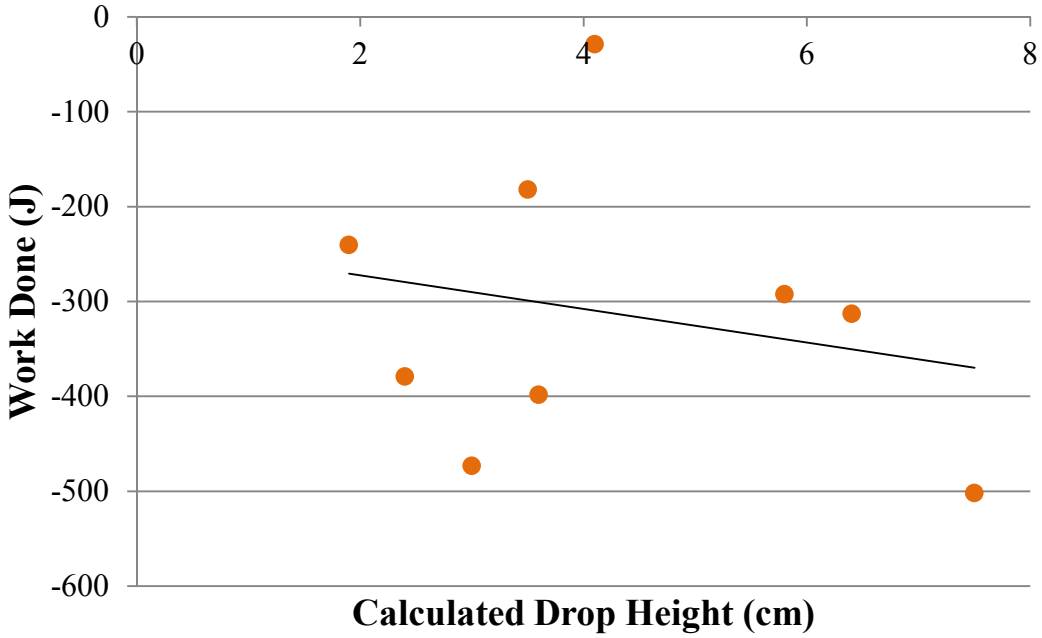


Figure 10.5: *Effect of Varying Drop Height on Work Done*

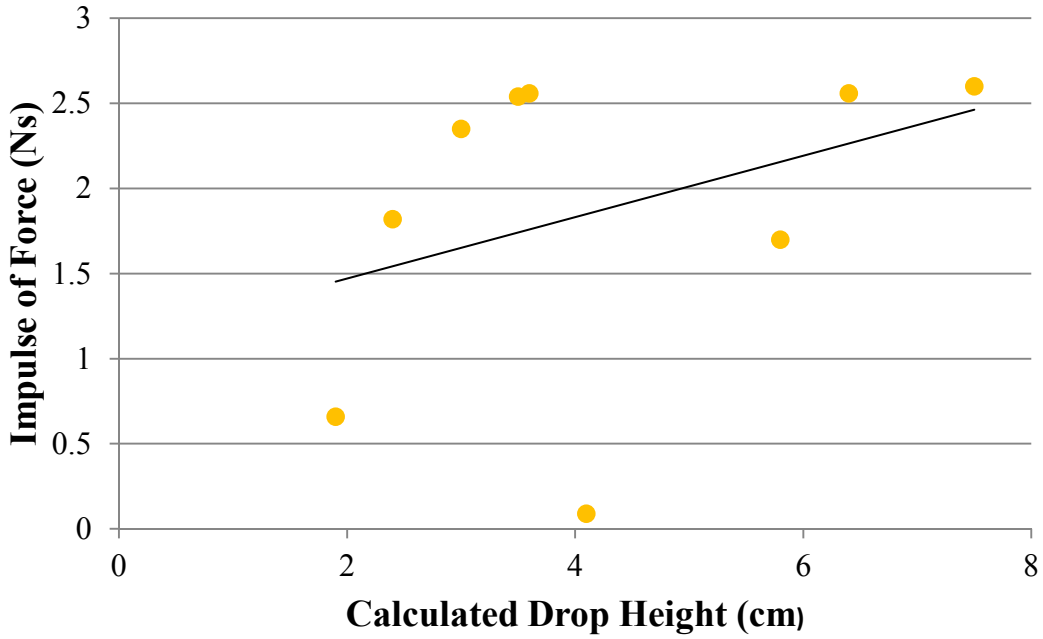


Figure 10.6: *Effect of Varying Drop Height on Impulse of Force*

10.2 Data Recording

The use of an accelerometer made data recording simple, with no need for the use of alternatives such as force plates. As the device is small and wireless, its attachment to the dropping mass was easy, it could be controlled via a computer thus there was no need to connecting wires.

10.3 Imaging

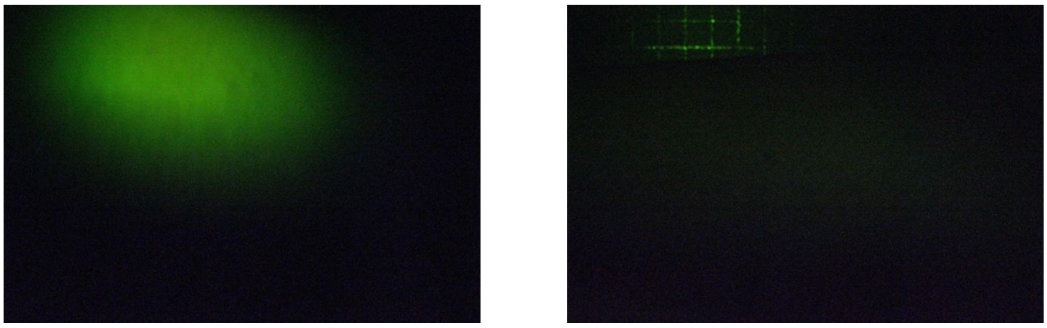
10.3.1 Timing of Imaging

The use of 24 hour intervals between imaging was useful in tracking the development and healing of a bruise, if formed. Images taken 2 hours after impact were also deemed beneficial as it showed any immediate discolouration formed from the applied forces. However, as in some instances there was no visible evidence of the impact after 2 hours (particularly for the lower impact forces), if this was to be repeated colour images would ideally have to be taken immediately after impact so that the specific impact areas could be documented for future reference.

10.3.2 Methods of Imaging

The colour imaging was the simplest of the three types used to perform. The use of the lighting stage made the replication of consistent photographic conditions possible. The only disadvantage noted was the lighting conditions. To the naked eye bruising could be identified, in some cases on both forearms. However, once the digital images were viewed on the computer, some bruises were not able to be identified (particularly faint bruising). This could have been due to the use of the light stand used to illuminate the forearm. If the lighting used was too bright, some bruising may have been unable obstructed and thus not able to be successfully imaged.

IR imaging was also simple to perform in that it made use of a digital camera where all that was required to adapt it to IR imaging was the attachment of a suitable filter. However, the use of the Quaser light source made the imaging process difficult. During the imaging process the light had to be passed along the length of the arm to ensure that the whole limb was illuminated, as the light guide itself was fairly narrow. As a result, the interpretation of the IR images was difficult as their clarity once transferred onto a computer reduced (Figure 10.7).



a. **b.**

Figure 10.7 *Examples of Unclear IR Images – a. Light Guide has Been Held too Close to the Forearm Resulting in a Small Area Being Illuminated b. Light Guide has Been Held too Far Away from the Forearm Resulting the Forearm Not Being Adequately Illuminated*

The images recorded from the camera were in a JPG format. This may have influenced the observations, as in this format the images are compressed causing a reduction in resolution. Ideally, RAW formatted imaged should have been used, as

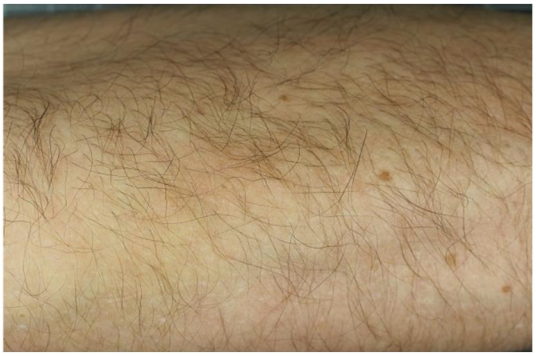
the data processing is minimal, thus resolution would not have been reduced (Farrugia 2011).

The imaging under UV conditions was the most difficult. The main difference was the in image quality between the digital camera and the images the VSC produced. The low number of pixels reduced the ability to visualise possible sites of bruising within the images. Furthermore, as the camera was located close to the surface of the arm, the ability of the VSC to focus on the skin surface was limited. As a result the slightest movement would cause blurring and no general images of the forearm as a whole could be taken.

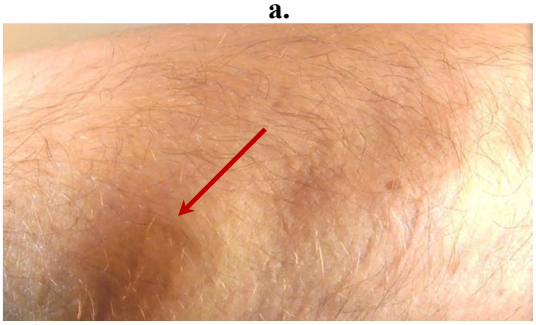
There was a UV lens available for the camera, however as the Quaser would have been required to produce the required lighting conditions, it was decided that this should not be done. This was based on the excitation filters available being unable to block the wavelengths of UV light which are considered harmful (254 nm and 312 nm) (Foster + Freeman 2012).

Shadows were also problematic, particularly at the proximal end of the forearm. These appeared to be a result of the close proximity of the forearm to the camera and due to the shape of the forearm, thus distinguishing between shadows and bruising was difficult. Figure 10.8 shows an example of where a possible bruise detected by the close-up image from the VSC under visible light turns out to be a large shadow, while Figure 10.9 shows an example of a positive identification of bruising, where definition is reduced by shadowing. Another possible cause for shadowing was that to image the arm, the side panels had to be held open. Therefore, the mirrors located on the inside of these panels are not able to reflect the light to evenly illuminate the forearm surface.

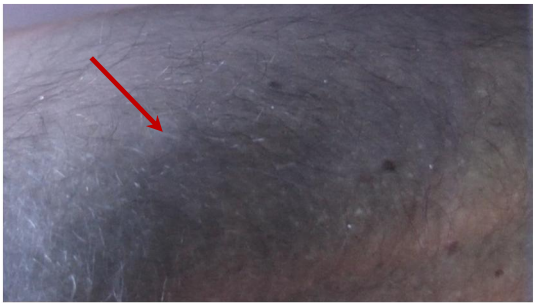
However, the VSC does have its advantages. Using the visible light settings some bruising could be identified which was not clear using the camera. Furthermore, its ability to switch between different light sources without the need for separate instrumentation or specific lighting conditions mean that if it could be adapted to be suitable for bruise imaging it could become a useful tool.



a.

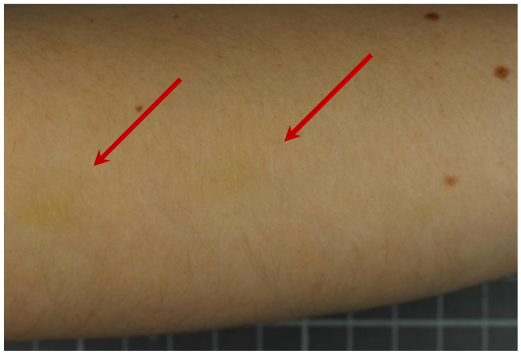


b.

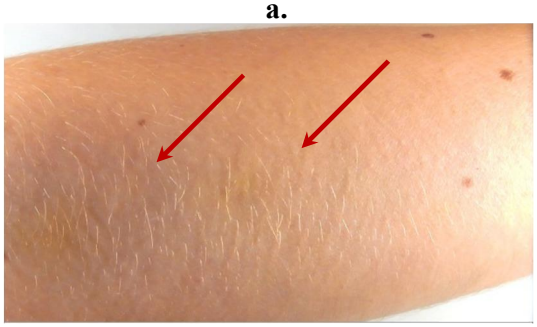


c.

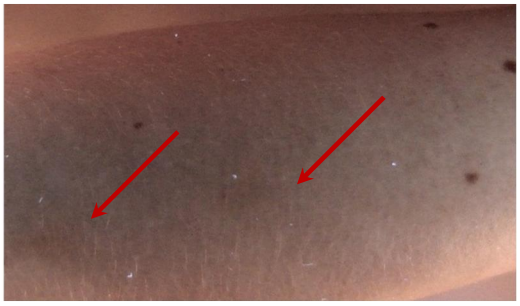
Figure 10.8: *Effects of Shadowing on Bruise Identification (6 Days After Impact)– a. Colour Image From The Digital Camera, No Visible Bruising b. Colour Image Using the VSC, Possible Bruising c. UV Image (No Colour Filters)Using VSC, Large Shadow Over Surface of Skin (Indicated by the Red Arrow)*



a.



b.



c.

Figure 10.9: *Effects of Shadowing on Bruise Identification (6 Days After Impact) – a. Colour Image From the Digital Camera, Two Locations of Bruising Visible b. Colour Image Using the VSC, Two Locations of Bruising Visible, The First of Which Appears to Surrounded by a Shadow c. UV Image (No Colour Filters), Two Locations of Bruising Identifiable, Not as Clear Definition Due to Shadow Over the Skin Surface*

11 Conclusions and Future Work

11.1 Study Conclusions

This study found that by applying a set of known impact forces to the forearm, the characteristic profiles for force, stress, velocity and displacement were similar across all participants. It was not possible to determine the minimum parameters required to initiate bruising. This was due to method inaccuracies and changing anatomy between participants, producing varying results. The application of a constant pressure for varying lengths of time was not successful in initiating bruising.

It was also not possible to determine a correlation between the colour ratios and bruise age and mechanical parameters of formation. The colours observed, although following the same general levels between participants, were only in tones of yellow making their relation to age difficult, as they are commonly associated with older bruises. No tones of red or blue were visually observed in the earlier stages of bruise development.

The use of colour imaging provided a useful method of documenting the timeline of a bruise, although influenced by skin colour. Standardizing these colour images provided a greater contrast between bruising and skin however, the depth and range of colours was lost.

IR imaging proved the least successful, with no positive results being able to be identified. This form of imaging was influenced by the light source used and its ability to evenly illuminate the forearm.

UV imaging, alone and with the application of filters, was successful in the imaging of bruising. However, this method was restricted by the light source and close proximity of the camera to the forearm.

For both IR and UV imaging, no non-visible characteristics were able to be identified after bruising appeared healed to the naked eye.

11.2 Future Work

For this work to be continued improvements to the versatility of the apparatus and dropping mechanism for the impacting masses would be recommended. Furthermore, a wider range of masses and/or drop heights would also be required.

Ensuring set locations for each impact and measurement of the fat and muscle content of the impact area would be required, as the gradient of the arm appeared to have an effect on the extent of bruising visualised.

The use of alternate light sources and different methods of image recording should be investigated with the aim of supporting or refuting recent studies which state success at identifying non-visible bruising. Furthermore, the ability to age bruises on their colour requires further investigation.

A larger pool of volunteers would be required to provide a greater range of results, with varying limbs being tested for comparison. Ideally an equal ratio of male to female participants should be used, with measurement of fat content within the limb being tested, documentation of their age and exercise habits would be required to assess the influence of these factors on the results produced.

Unfortunately due to apparatus availability, it was not possible to obtain daily results for each participant. Furthermore, participants were also not expected to return over the weekends for images to be taken. Thus, to gain a complete photographic log of bruise development and healing, daily photography must be carried out.

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Appendix 1

Ethics Form

1. Title of the investigation
Biomechanics of Bruising

2. Chief Investigator (Ordinance 16 member of staff only)
Name: Dr. Philip Riches Status: ☐ Professor ☐ Reader ☐ Senior Lecturer ☒ Lecturer Department: Biomedical Engineering Telephone: 0141 548 5703 E-mail: philip.riches@strath.ac.uk

3. Other Strathclyde investigator(s)
Name: Prof. Niamh NicDaéid Status (e.g. lecturer, post-/undergraduate): Professor Department: Centre of Forensic Science Telephone: 0141 548 4700 E-mail: n.nicdaeid@strath.ac.uk Name: Heather Black Status (e.g. lecturer, post-/undergraduate): MSc Student Department: Biomedical Engineering Telephone: 07745251659 E-mail: gxb12163@uni.strath.ac.uk

4. Non-Strathclyde collaborating investigator(s)
Name: Status (e.g. lecturer, post-/undergraduate): Department/Institution: If student(s), name of supervisor: Telephone: E-mail: Please provide details for all investigators involved in the study:

5. Overseas Supervisor(s)
Name(s): Status: Department/Institution: Telephone: Email: I can confirm that the local supervisor has obtained a copy of the Code of Practice: Yes ☐ No ☐ Please provide details for all supervisors involved in the study:

6. Where will the investigation be conducted
Biomedical Engineering Wolfson Centre University of Strathclyde 106 Rottenrow Glasgow G1 0NW

7. Duration of the investigation
Duration(years/months) : 4 months Start date (expected): 27 / 06 / 2013 Completion date (expected): 13 / 08 / 2013

8. Sponsor (please refer to Section C and Annex 3 of the Code of Practice):
University of Strathclyde

9. Funding body (if applicable)

Name of funding body:

Status of proposal – if seeking funding (please click appropriate box):

☐ In preparation

☐ Submitted

☐ Accepted

Date of Submission of proposal: / /

Date of start of funding: / /

10. Objectives of investigation (including the academic rationale and justification for the investigation)

Identifying and determining the age of a bruise during forensic investigations is a useful means of supporting or refuting a claim of abuse which has resulted in physical injury. This becomes more important in cases involving victims who may be unable to communicate the time at which they received their injuries or how they received them.

The current standard method of visual assessment of a bruise is considered unreliable as it is highly subjective: the method is entirely opinion-based, with varying expert views on which bruising characteristics are of most relevance to its age (e.g. colour variation and intensity, size or if swelling is present). A study into the reliability of forensic expert estimations asked 23 experts to estimate the age of 25 bruises. Of the total 575 estimations made, only 4 age estimations were correct (Grossman et al. 2011).

A study in 2002 asked 3 health professionals (a doctor, nurse and medical student) to describe which colours they perceived in 58 bruises both on the child *in vivo* and in photographs at a later date. Of the 58 bruises at the *in vivo*, only 6 were in complete agreement (i.e. exact colour match description) between the 3 observers. When assessing the photographs only 4 bruises were found to be in complete agreement and when comparing the *in vivo* and photographic assessment, only 1 bruise was found to be in complete agreement between all 3 observers. Although this study focused on health professionals, it highlights the inaccuracies of human colour perception (Munang, Leonard and Mok 2002).

Another colour study asked a selection of emergency physicians, other qualified physicians and trainee physicians to assess bruises found on children up to the age of 18, with the aim to determine if it is possible to predict the age of a bruise via physical examination. The study found that for all 3 physician groups, the success of aging the bruise was always below 50%. A summary of their percentage findings is shown in the table below (Bariciak et al. 2003).

Physician Group	**Percentage of Estimations Within 24 Hours of True Bruise Age**
Emergency	47.6
Other Qualified	29.4
Trainee	36.8

Although there is a wide range of opinions on which colours should be used in the aging a bruise, it is widely accepted that the colour yellow is significantly important as it is only found within older bruises (>48 hours). In 2004, a study was carried out on 50 volunteers investigating the level of colour

perception. Each volunteer was shown various images of a bruise, which had been digitally altered to contain increasing percentages of yellow (0%-20%). Once the volunteer stated they could see yellow within the image, the percentage was recorded. The study found that perception ranged between 4% and 16% yellow concentration. This highlights how inconsistent visual colour discrimination is by the human eye and thus the inaccuracies in expert interpretations, as the level of colour perception will undoubtedly vary between experts. This further indicates the issues surrounding bruise colour perception on victims of varying skin colour (Hughes, Ellis and Langlois 2004; Maguire et al. 2005).

Another concern with visual assessment by experts in cases where they are presented with a photograph rather than an *in vivo* bruise is that the photograph can be misleading. The 2D image loses any contours or swelling associated with a bruise. Thus, if an expert bases their opinion upon these characteristics, their interpretation will be inaccurate (Maguire et al. 2005).

To rectify the issues surrounding visual analysis, various techniques have been tried. Using a combination of spectroscopy measurements and computer modelling, Kim et al. in 2012 attempted to understand the changing composition of aging bruises. They recorded the concentrations of bilirubin, blood oxygenation and blood volume fraction using spectrometry, showing that their levels would peak at various stages throughout the bruise timeline. Specifically, bilirubin peaked at 80 hour and this value along with those for the other parameters were then applied in the formation of a computer model. This model represented the epidermis, dermis and subcutaneous tissue layers of the skin. However, although tracking bilirubin levels could be useful understanding a bruise timeline, their modelling of the skin and thus their representation of what happens during bruise formation and healing is false. The authors themselves acknowledge that their model was too basic and that it did not take into consideration blood flow. Furthermore, their method becomes impractical within a forensic context. The spectroscopy does not factor in any medical or physical factors which could increase bleeding or reduce healing time and thus the levels of bilirubin you would expect to see would vary. Also, to continually take measurements over a period of time after a claim of abuse to generate a bruise profile would be difficult to perform.

Another method which has been attempted in the characterisation of bruises is through the use of ultrasound imaging. In 2012, Mimasaka, Oshima and Ohtani investigated using ultrasound to measure depth and thickness of 10 bruises in forensic autopsy cases, then comparing the results with macroscopic investigation. They also used the ultrasound analysis on 16 bruises present on 8 volunteer children. They found a good correlation between using ultrasound and the measurements obtained during autopsy and that this technique could be used on living volunteers. However, allow a potential method for non-invasive, accurate evaluation of depth and thickness, the study does highlight the difficulties in interpreting the image, thus measurement errors cannot be eliminated. Furthermore, it is unknown what effect ultrasound has on bruise shape. It may cause the pooled blood to disperse giving a false representation of its true shape and thus any interpretation on the force which would have been responsible to form the bruise would be inaccurate.

There have been more successful attempts to improve the visual analysis of a bruise. The use of infrared photography was used by Rowan et al. in 2010 in an attempt to identify sites of bruising when the bruise itself is no longer visible to the naked eye. Of all the bruises they photographed, only one was still visible using infrared imaging when no longer visible to the eye. Although they only obtained one positive result, their findings highlight the potential for the use of alternative photography. Furthermore, the potential for investigating the non-visible characteristics associated with bruise development and their relationship with the size of impact force could be possible. This would then lead to supporting or refuting claims of assault at the time of incident, before a distinctive bruise has formed.

Another approach to objectify visual analysis was also carried out by Grossman et al. in 2011. They used a vacuum pump to produce bruises on volunteers and then took colour photographs under standard conditions daily until the bruise was no longer visible. They then used Photoshop to standardize the photographs and measure the red, green and blue (RGB) values, tracking their levels and ratios to each other during the bruise timeline. Unfortunately their results were not very successful, with the only correlation between bruises being visible in the comparison of two bruises

located on the same person. However, there is potential for this to be improved on. Their method involved digital standardization and standardized photography conditions and camera settings. This resulted in some of the photographs becoming either under or over exposed and thus unable to be used, with the other images being over-manipulated. Furthermore, their method of bruise formation does not represent how bruises are formed during a physical assault. If this method could be replicated, with a more realistic method of bruise formation and more appropriate photography standardization, the measurement of RBG ratios has the potential to be valuable in the evaluation of bruising characteristics and bruise age.

The mechanical parameters of subcutaneous bruise formation have rarely been investigated. One such study (Desmoulin and Anderson, 2011) involved a single participant being subject to six 1.9kg mass and six 2.6kg mass impacts at various locations on their legs. Using a force plate and potentiometer, a force profile for each impact was produced, from which mechanical parameters including pressure, tissue stiffness and absorbed energy could be inferred and any relationship between the parameters and bruise formation could be determined. They found that where the tissue was stiffest, there was a greater chance of bruise formation. However, although useful, there data does only relates to one individual, thus their findings cannot be stated as true for the population as a whole. Therefore, there is an urgent need for this type of investigation to be expanded on, testing various limbs, thus confirming or refuting their findings and providing valuable published data in this field.

The objective of this study is therefore to assess the mechanical parameters surrounding the formation of a bruise and to determine if there is any correlation between the ratios of colours present (rather than the range or intensity) and the bruise age. Furthermore, we wish to explore the timeline stages of bruise formation and healing. This would be investigated through analysis of the effects of a known force profile upon a limb and the use of infra-red imaging to visualise any non-visible characteristics.

References:

BARICIAK, E., et al., 2003. Dating of Bruises in Children: An Assessment of Physician Accuracy. *Pediatrics: Official Journal of the American Academy of Pediatrics*, 112 (4), pp. 804-807.

DESMOULIN, G. T. and ANDERSON, G. S., 2011. Method to Investigate Contusion Mechanics in Living Humans. *Journal of Forensic Biomechanics*, 2, pp. 1-10.

GROSSMAN, S.E., et al., 2011. Can we Assess the Age of Bruises? An Attempt to Develop an Objective Technique. *Medicine, Science and the Law*, 51, pp. 170-176.

HUGHES, V. K., ELLIS, P. S. and LANGLOIS, N. E. I., 2004. The Perception of Yellow in Bruises. *Journal of Clinical Forensic Medicine*, 11, pp. 257-259.

KIM, O., et al., 2012. Reflectance Spectrometry of Normal and Bruised Human Skins: Experiments and Modeling. *Physiological Measurement*, 33, pp. 159-175.

MAGUIRE, S., et al., 2005. Can You Age Bruises Accurately in Children? A systematic Review. *British Medical Journal*, 90, pp. 187-189.

MIMASAKA, S., OSHIMA, T and OHTANI, M., 2012. Characterization of Bruises Using Ultrasonography for Potential Application in Diagnosis of Child Abuse. *Legal Medicine*, 14, pp. 6-10.

MUNANG, L. A., LEONARD, P. A. and MOK, J. Y. Q., 2002. Lack of Agreement on Colour Description Between Clinicians Examining Childhood Bruising. *Journal of Clinical Forensic Medicine*, 9, pp. 171-174.

ROWAN, P. et al., 2010. The Use of Infrared Aided Photography in Identification of Sites of Bruises After Evidence of the Bruise is Absent to the Naked Eye. *Journal of Forensic and Legal Medicine*, 17, pp. 293-297.

11. Nature of the participants

Please note that investigations governed by the Code of Practice that involve any of the types of projects listed in B1(b) must be submitted to the University Ethics Committee for prior approval

Are any of the categories mentioned in Section B1(b) (participant considerations) applicable in this investigation?

☐ Yes

☒ No

Please detail nature of participants: Healthy adults

Number: Minimum of 5 Age (range): 18 to 45

Please also include information on: recruitment methods (see section B4 of the Code of Practice); inclusion/exclusion criteria; and any further screening procedure to be used

Recruitment Methods:

Volunteers will be invited to take part via an email invite. This will be sent to students and staff of the University of Strathclyde from Departmental lists.

Exclusion criteria for this study:

- Those who suffer from haemophilia, alcoholism, heart disease, cancer, chronic lower respiratory disease, Alzheimer's disease, diabetes, nephritis or have suffered a stroke.
- Those at higher risk of blood clot formation i.e. if considered medically obese (BMI >30), medically underweight (BMI<19) pregnant, a smoker or have a family history of inherited clotting disorders.
- Those who have suffered a musculoskeletal pathology trauma or have deformity of the arms.
- Currently on any medication or drug (prescribed or non-prescribed).
- Currently taking aspirin
- Currently taking any herbal remedies or dietary supplements, for example ginko biloba.
- Presence of identifying marks, tattoos and/or piercings on forearms.
- No alcohol intake 24 hours prior to study.

12. What consents will be sought and how?

Please note that the information sheets and consent forms to be used should be attached to this form

Full informed consent will be sought (see attached PIS)

13.Methodology

Investigations governed by the Code of Practice that involve any of the types of projects listed in B1(a) must be submitted to the University Ethics Committee for prior approval. Where an independent reviewer is not used, then the UEC/ DEC reserves the right to scrutinise the methodology.

Are any of the categories mentioned in the Code of Practice Section B1(a) (project considerations) applicable in this investigation?

☒ Yes

☐ No

If 'yes' please detail: Study will involve harm and discomfort of a physical nature

Design: what kind of design/research method(s) is/are to be used in the investigation? Research Study

Potential participants will be provided with a Participant Information Sheet and a short health questionnaire via email. If the reply stating they are willing to volunteer, they will be invited to meet the researcher to discuss any concerns and where any questions will be answered. Eligibility to participate will be confirmed by the volunteer and then they will freely sign the consent form under no obligation.

The investigation will involve the participant having the anterior face of their forearm photographed using both colour and infra-red cameras. These images will be used as reference images. The participant will then be subject to 3 impact forces on their forearm. From this, a force profile will be generated allowing for the determination of the mechanical parameters required for bruise formation to be determined. These parameters include impact force and pressure, force impulse and pressure impulse. Limb characteristics such as tissue stiffness and energy absorption will also be calculated to determine their effect on bruise formation.

Each participant will be invited to return to Biomedical Engineering on a daily basis. This is for photography of the bruise development and healing. This observation is expected to last approximately 2-3 weeks, until the bruises are no longer visible using infra-red imaging.

Techniques: what specific techniques will be employed and what exactly is required of participants?

Impact Force Production

Participants will be asked to place their arm through a gap in a screen which conceals the experimental apparatus from view. Once in place, three varying masses will be dropped onto the forearm. Both masses and drop height will be determined through a pilot study (discussed at the end of this section) however, they are not expected to exceed 5 kg or 17 cm respectively. The moment of mass release will not be known to the participant to avoid muscle tensing.

The apparatus itself will consist of a small aluminium, cylindrical impactor (~2 cm diameter), with a padded base which will rest on the surface of the forearm. Varying masses of mild steel will be dropped onto this impactor on different locations on the forearm surface, down a secured tube from a set height. The impactor will also be secured in place within this tubing. The mass will have a 10g accelerometer attached, operating at 1000 Hz. This will be used to determine the impact force variation with time.

Photography

Photography will be carried out regularly throughout the duration of the study. Participants will be required to have their arm photographed daily during this study, using both colour and infra-red imaging. Photography lighting conditions will remain constant each time (i.e. not in sunlight) with camera settings being set individually for each photograph to minimise the risk of under and/or over exposure. The photographs will be taken at approximately the same time the impact force was applied on the initial day of the study, generating a visual representation of the development and healing of the bruise.

The colour images will be analysed through the use of Photoshop to determine the ratio of red, green and blue colours present within the bruise. The infra-red images will be used to determine if there are any non-visible characteristics and if bruises can be identified if no longer visible to the naked eye

Pilot Study

Using the apparatus design stated above, the impact time, drop height and impactor mass criteria will be determined. Based on a previous study, the minimum pressure required to form a bruise on one person's lower leg is 1720 kPa (Desmoulin and Anderson 2011).

The pilot study will be conducted by the researchers on the other named researchers in this proposal. Masses varying from 3.4kg to 5kg will be dropped onto the forearm from heights between 11cm and 17cm. These have been selected as calculations have shown that they will maintain accelerations below 10g (i.e. 98.1 m/s^2, a necessary requirement of the equipment we are using) whilst producing impact forces and pressures expected to initiate bruise formation. In these calculations it is assumed that impact times of 0.04 seconds and 0.05 seconds will occur. These timings have been verified by preliminary (pre-pilot test) findings on the chief investigator, and are consistent with other impact scenarios, e.g. heading a football.

Bruise formation will be noted and a range of experimental parameters that form a bruise will be utilised in the main study.

References

DESMOULIN, G. T. and ANDERSON, G. S., 2011. Method to Investigate Contusion Mechanics in Living Humans. *Journal of Forensic Biomechanics*, 2, pp. 1-10.

Has this methodology been subject to independent scrutiny?

☐ Yes

☒ No

Please provide the name and contact details of the independent reviewer:

14. Data collection, storage and security

Explain how data are handled, specifying whether it will be fully anonymised, pseudo-anonymised, or just confidential, and whether it will be securely destroyed after use:

Personal details (name, address and contact details) will be used to contact the participants, arranging time of study and to inform of any alterations to the study arrangements.

The data will be pseudo-anonymised (i.e. coded identification) and will be retained until project completion, on which personal information will be deleted or shredded, but the now fully anonymised data will be kept indefinitely in the filing cabinet of the chief investigator.

Explain how and where it will be stored, who has access to it, and how long it will be stored: The pseudo-anonymised data will be stored on password protected University computers.

Will anyone other than the named investigators have access to the data? Yes ☐ No ☒
If 'yes' please explain:

15. Potential risks or hazards

The participant will experience pain and discomfort immediately and/or over a short period of time after the experiment has been carried out. .

The pain and discomfort cannot be reduced as it is experienced at different levels by individuals. To reduce the possibility of musculoskeletal damage or effects of increased/reduced blood clotting ability, only volunteers who do not fall within the exclusion criteria outlined within Question 11 of this form will be asked to participate.

16. Ethical issues

The participant will experience physical harm whilst being unaware of the exact moment of impact.

This issue is addressed through the participant being made fully aware the purpose of the study, all risks involved and with them providing informed consent before taking part.

17. Any payment to be made

No, participation in this project is voluntary

If requested, participants will be provided will an electronic copy of the final thesis

18. What debriefing, if any, will be given to participants

Participants will be given full disclosure of the purpose of the study and information on what the findings will aim to achieve.

19. How will the outcomes of the study be disseminated (will you seek to publish the results)
The results of the investigation will be published in an MSc thesis.

20. Nominated person to whom participants' concerns/ questions should be directed before, during or after the investigation (please also provide contact details)	
Heather Black Biomedical Engineering Unit University of Strathclyde 106 Rottenrow Wolfson Centre Glasgow G1 0NW 07851789861 gxb12163@uni.strath.ac.uk	Dr. Philip Riches (Supervisor) Biomedical Engineering Unit University of Strathclyde 106 Rottenrow Wolfson Centre Glasgow G1 0NW 0141 548 5703 philip.riches@strath.ac.uk
Prof Niamh NicDaéid (Supervisor) Centre of Forensic Science 204 George Street, Royal College Building Glasgow G1 1XW 0141 548 4700 n.nicdaeid@strath.ac.uk	

21. Previous experience of the investigator(s) with the procedures involved
Dr. Philip Riches has previous experience of research into the mechanical behaviour of tissue, clinical and sports biomechanics. Prof Niamh NicDaéid has previous experience in research within a forensic context and currently works with international forensic societies. Both investigators have jointly worked on investigating the effects of varying impact pressures on the production of footwear impressions, combining both forensic methodology and mechanical parameter investigation.

Checklist	Enclosed	N/A
Participant Information Sheet(s)	☒	☐
Consent Form(s)	☒	☐
Sample questionnaire(s)	☒	☐
Sample interview format(s)	☐	☒
Sample advertisement(s)	☐	☒
Any other documents (please specify below)		
	☐	☐
	☐	☐
	☐	☐
	☐	☐
	☐	☐

22. Chief Investigator and Head of Department Declaration
Please note that unsigned applications will not be accepted and both signatures are required

I have read the University's Code of Practice on Investigations involving Human Beings and have completed this application accordingly.

Signature of Chief Investigator

Please also type name here:

I confirm I have read this application, I am happy that the study is consistent with departmental strategy, that the staff and/or students involved have the appropriate expertise to undertake the study, that the study makes appropriate use of available resources and facilities within the department and that there are no other departmental-specific issues relating to the study of which I am aware

Signature of Head of Department

Please also type name here

Date: / /

23. Only for University sponsored projects under the remit of the DEC/SEC, with no external funding and no NHS involvement

Head of Department statement on Sponsorship

This application requires the University to sponsor the investigation. This is done by the Head of Department for all DEC applications with exception of those that are externally funded and those which are connected to the NHS (those exceptions should be submitted to R&KES). I am aware of the implications of University sponsorship of the investigation and have assessed this investigation with respect to sponsorship and management risk. As this particular investigation is within the remit of the DEC and has no external funding and no NHS involvement, I agree on behalf of the University that the University is the appropriate sponsor of the investigation and there are no management risks posed by the investigation.

If not applicable, click here ☐

Signature of Head of Department

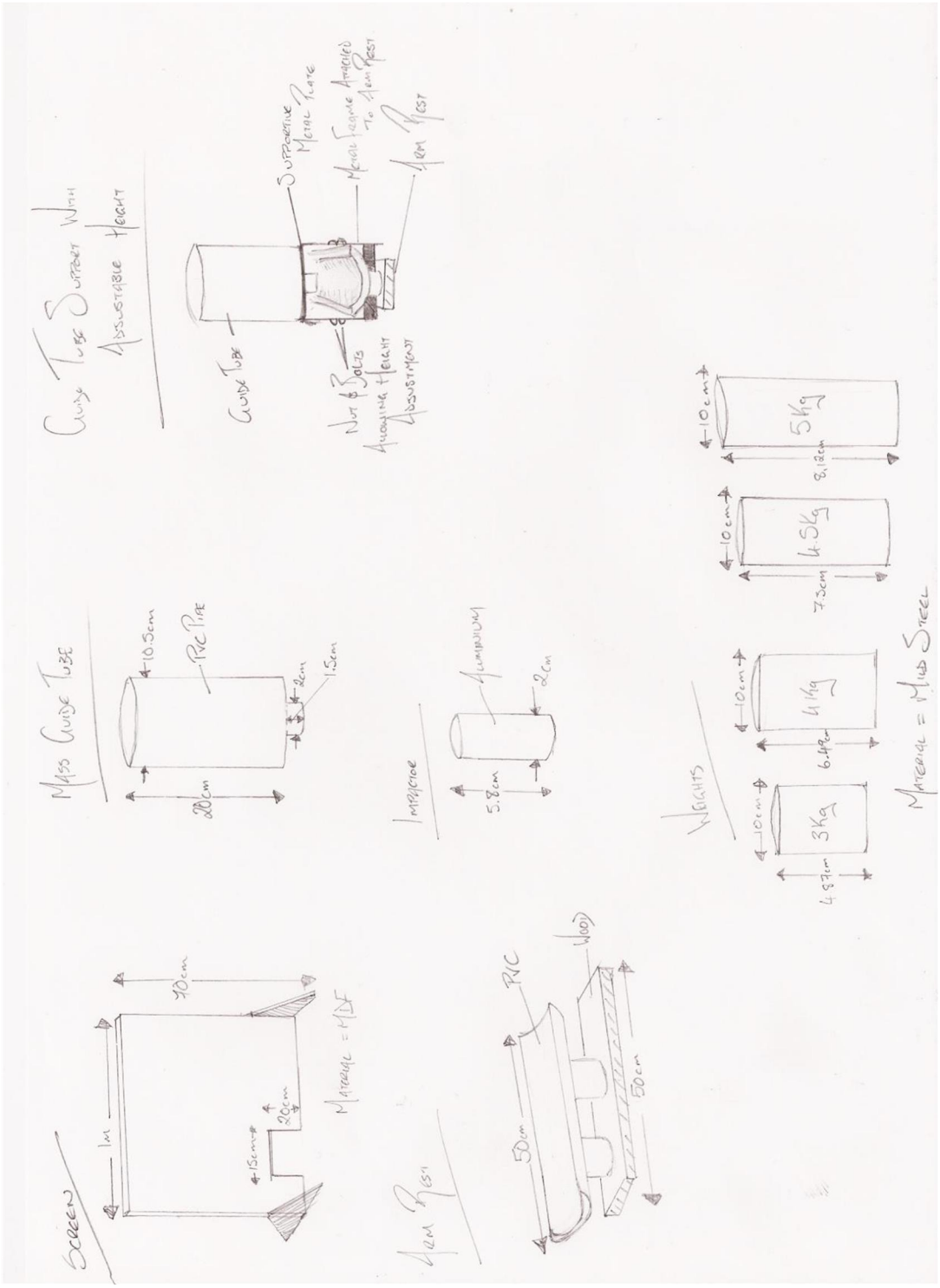
Please also type name here

Date: / /

For applications to the University Ethics Committee the completed form should be sent to ethics@strath.ac.uk with the relevant electronic signatures.

Appendix 2

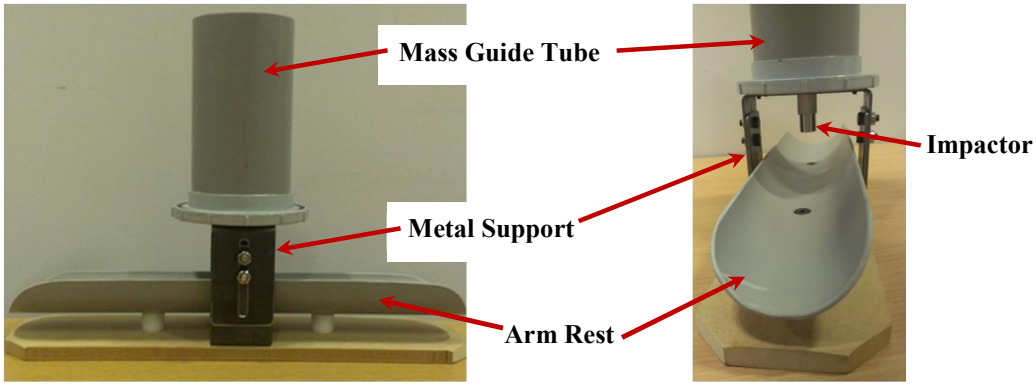
Rig Design Drawings



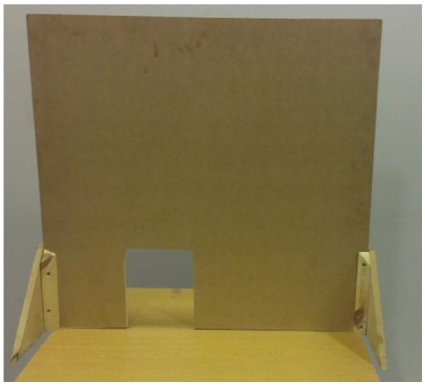
Note: During production, the dimensions of some components were altered due to the materials available.

Appendix 3

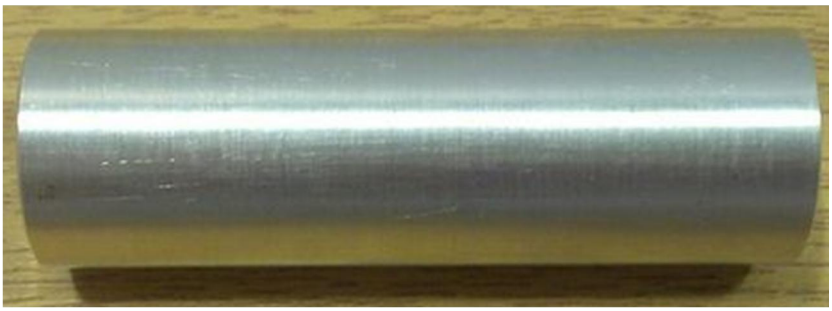
Images of Built Rig Components



A.1: *Mass Guide Tube with Impactor, Arm Rest and Metal Support with Adjustable Height*



A.2: *MDF Screen*



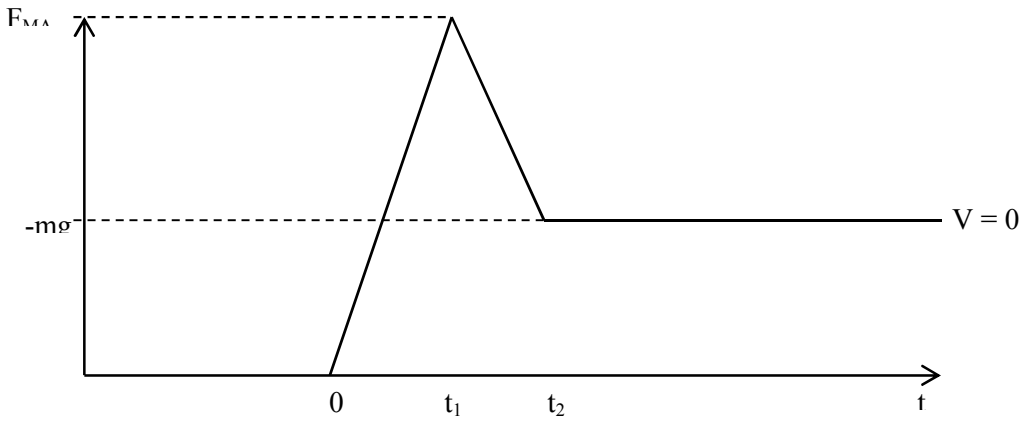
A.3: *Aluminium Impactor*

A.4: *2.7 kg Mass – Mild Steel*

A.5: *4.8 kg Mass – Mild Steel*

Appendix 4

Drop Height Calculations Using Preliminary Testing Force Profile



Equation Derivitisation

Maximum Deceleration at t_1

Impact Time = 0→t_2 At 0, Velocity = $V_o = -\sqrt{-2gh}$

$$\Delta V = V - V_o$$

$$\Delta V = 0 - V_o$$

$$\Delta V = 0 - -\sqrt{-2gh}$$

$$\Delta V = \sqrt{-2gh}$$

$$F + mg = ma \longrightarrow F + mg = m\frac{dV}{dt}$$

$$\frac{F}{m} + g = \frac{dV}{dt}$$

Integrating $\longrightarrow$ $\frac{1}{m}\int_0^t F dt + \int_0^t g = \int_{V_0}^0 dV$

$$\frac{1}{m}\int_0^t F dt + gt = V_0$$

$$\frac{1}{m}\int_0^t F dt + gt = \sqrt{-2gh}$$

Therefore Using the Force Profile:

$$\int_0^t F dt = \frac{1}{2}(t_1 - 0)F_{MAX} + \frac{1}{2}(t_2 - t_1)(F_{MAX} + mg) + (t_2 - t_1)(-mg) + (t - t_2)(-mg)$$

This is be Simplified to:

$$\frac{-1}{2g}\left[\frac{1}{2m}t_2 F_{MAX} + \frac{1}{2}(t_1 + t_2)\right]^2 = h \qquad \textbf{Eqn. 1}$$

$$F + mg = ma \longrightarrow F_{MAX} + mg = ma_{MAX}$$

$$a_{MAX} = \frac{1}{m}F_{MAX} + g$$

Taking an $a_{MAX}$of -8g:

$$\frac{1}{m}F_{MAX} + g = -8g$$

$$F_{MAX} = -9mg \qquad \textbf{Eqn. 2}$$

Substituting Eqn. 2 into Eqn. 1:

$$\frac{-1}{2g}\left[\frac{1}{2m}t_2(-9mg) + \frac{1}{2}(t_1 + t_2)\right]^2 = h$$

Which Can then Be Simplified to:

$$\frac{-1}{2g}\left(\frac{1}{2}gt_1 - 4gt_2\right)^2 = h \qquad \textbf{Eqn. 3}$$

Experimentally, $t_1 = 0.025$ and $t_2 = 0.05$, thus $t_1 = \frac{1}{2}t_2$

Therefore for drop height:

$$\frac{-1}{2g}\left(\frac{15}{4}gt_2\right)^2 = h \qquad \textbf{Eqn. 4}$$

Height Calculation

Using Eqn. 4, impact times (t_2) of 0.04 s and 0.05 s were used, thus drop heighs were calculated to be 11 cm and 17 cm respectively.

Appendix 5

Calculations for Calculating the Masses to be Dropped

Lowest Values Which Produces a Bruise in the Study by Desmoulin and Anderson in 2011:

Peak Force (N)	Impacted Area (m^2)	Peak Pressure (kPa) = Force/Area	Peak Pressure (kPa) Stated in Study
342	0.0002	1710	1720

As this investigation is going to be looking at the forearm and not the lower leg, the pressure values required to induce a bruise would be expected to be lower.

The 2 cm impactor gives an impacting area of 0.000314 m^2.

Looking at a range of masses between 1 and 5 kg the following forces (using Eqn. 2 from Appendix 1) and peak pressures (using Force/Impactor Area) were calculated:

Mass (kg)	Force (N)	Peak Pressure (kPa)
1.0	88.29	281.04
1.5	132.44	421.55
2.0	176.58	562.07
2.5	220.73	702.59
3.0	264.87	843.11
3.5	309.02	983.63
4.0	353.16	1124.14
4.5	397.31	1264.66
5.0	441.45	1405.18

From these values, the masses of 3 kg, 4 kg, 4.5 kg and 5 kg were deemed as suitable for use within the pilot study (This was later changed to only 2.7 kg being dropped).

Appendix 6

Participant Information Sheet

Name of department: Biomedical Engineering

Title of the study: Biomechanics of Bruising

Dear volunteer,

You are being asked to participate in a study that is being conducted by the University of Strathclyde and has been subjected to ethical approval by the University Ethics Committee.

The objective of this study is to understand the mechanical parameters surrounding the formation of a bruise. The study also aims to assess if there is any correlation between the colour changes of a bruise and the passage of time, whilst also investigating the ability to identify bruising characteristics not visible to the naked eye.

Little is known about the mechanical characterisation of bruise formation and this research could develop a link between the physical appearance of a bruise with an estimated force and time of creation. If successful, this research would have an impact in forensic science in the validation of assault timelines.

It is necessary in this research to inflict pain, and we fully understand any reticence in volunteering. However, we are fully committed to answering these important questions, and if there is a way to do this without causing pain we would obviously follow that route. We believe that this information sheet describes an important experiment and we hope that you understand our belief that the potential long term benefits of this work outweigh the short-term pain. The experiment has been piloted on the supervisors, and we would not put you in any position that we are not willing to be in ourselves.

This information sheet hopefully provides a clear explanation of the study including the research aims, benefits, risks and also what participation would mean for yourself and any implications concerning your involvement. If there is any aspect of the study which is unclear that you would like further information on, please contact me or either of my supervisors who will be happy to answer your questions. Our contact details can be found at the end of this information sheet.

Thank you for your time.

Heather Black

MSc Biomedical Engineering Student

What is the purpose of this investigation?

The objective of this study is to understand the mechanical parameters surrounding the formation of a bruise including the force of impact and velocity of impact required. The study also aims to objectively assess the colour characteristics observed (range and intensity) and determine any non-visible characteristics over an approximate 3 week time period.

Do you have to take part?

No. Participation is entirely voluntary and will require a significant commitment on your behalf. If you decide to participate you will be asked to sign a form to confirm that the study was clearly explained to yourself, and that you agree to take part. You will be free to withdraw at any time without giving a reason. The relationship you have with the University will not be affected in any way should you withdraw yourself, or your data, from the study.

What will you do in the project?

Over an approximate 3 week period you will be required to attend the Forensic Science Department in the Royal College Building on a daily basis at the same time. On the initial day of the study, your forearm will be subject to three impact forces, with photographs of the arm being taken before and after impact. During the procedure the apparatus will be hidden from view so you will not know when the impact will occur. On your other forearm, a constant pressure will be applied three times and held in place for 15, 30 and 60 seconds.

For the remaining time period of the study, you will be required to attend the department for daily photographs of your arm. As bruises do not heal over a set number of days you will only be required to return until the bruise (if one has formed), has fully healed. You will not be required to return over the weekends.

There will be no monetary payment for taking part however, you may receive an electronic copy of the final thesis if you wish.

What are the potential risks to you in taking part?

During the study you will experience immediate and/or short term pain and discomfort. The pain experienced should feel similar to a focussed punch, or at worst, similar to a ‘dead arm’ It is the intention to create bruises that last a number of days which requires some damage to be made to the musculature. Providing that you have had no unusual bruising in the past, there is no long term risk of you taking part.

What happens to the information in the project?

All personal details will remain confidential and all results will be anonymous, identifiable through a coded system. All information will be stored on password protected University computers and all

personal details will be deleted/destroyed once the study is complete. Anonymised electronic data, including photographs, will be kept indefinitely by the University by both my supervisors for potential further use. I will not keep any photographs once the thesis is submitted.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

What happens next?

If you would like to take part in the study you will be asked to fill in a short questionnaire confirming you are eligible to participate in the study. Following this, if applicable, you will be asked to sign a consent form to confirm you are happy to proceed.

If however, you decide you do not wish to be involved in this study, I thank you for your time and consideration.

Researcher Contact Details:

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This investigation was granted ethical approval by the University of Strathclyde ethics committee.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Secretary to the University Ethics Committee

Research & Knowledge Exchange Services

University of Strathclyde

Graham Hills Building

50 George Street

Glasgow
G1 1QE

Telephone: 0141 548 3707

Email: ethics@strath.ac.uk

Participant Questionnaire

Please indicate whether any of the mentioned conditions below apply to you, by circling yes or no below.

Do you suffer from haemophilia?	**Yes No**
Do you suffer from alcoholism?	**Yes No**
Do you suffer from heart disease?	**Yes No**
Do you suffer from cancer?	**Yes No**
Do you suffer from chronic lower respiratory disease (e.g. asthma or emphysema)?	**Yes No**
Do you suffer from Alzheimer's disease?	**Yes No**
Do you suffer from diabetes?	**Yes No**
Do you suffer from nephritis (inflammation of the kidney)?	**Yes No**
Have you had a stroke?	**Yes No**
Are you medically obese (BMI greater than 30)?	**Yes No**
Are you medically underweight (BMI less than 19)?	**Yes No**
Are you currently pregnant?	**Yes No**
Are you currently a smoker?	**Yes No**
Do you have a family history of blood clotting disorders?	**Yes No**
Have you suffered a musculoskeletal pathology disorder to the forearm (e.g. broken or fractured bones, muscular disease)?	**Yes No**
Do you suffer from a deformity of the arms?	**Yes No**
Are you currently on **any** prescribed or non-prescribed medication or drug?	**Yes No**
Are you currently taking aspirin?	**Yes No**
Are you currently taking **any** herbal remedies or dietry supplements (e.g. ginko biloba)?	**Yes No**
Do you have any identifying marks, tattoos and/or piercings on forearms?	**Yes No**
Have you consumed any alcohol in the previous 24 hours?	**Yes No**

If you **<u>have</u>** answered 'yes' to any of the above, unfortunately you are unable to participate in this study.

If you **<u>have not</u>** answered 'yes' to any of the above, please continue onto the consent form.

Appendix 7

Consent Form

Name of department: Biomedical Engineering

Title of the study: Biomechanics of Bruising

- I confirm that I have read and understood the information sheet for the above project, that I have had time to reflect and consider my participation, and that the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to photographs of my arm being taken.
- I confirm that I am available every day for approximately the next 3 weeks.
- I confirm that I am within the ages of 18 to 45.
- I confirm that all details I have provided on the participant questionnaire are correct to the best of my knowledge.
- I consent to being a participant in the project.

(PRINT NAME)	Hereby agree to take part in the above project
Signature of Participant:	Date