UNIVERSITY OF SOUTHAMPTON

FACULTY OF MEDICINE

Institute of Developmental Sciences

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An investigation of mechanisms determining depth of chest compression during a simulated in-hospital cardiac arrest

by

Richard Bain

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ABSTRACT

FACULTY OF MEDICINE

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Thesis for the degree of Doctor of Philosophy

An investigation of mechanisms determining depth of chest compression during a simulated in-hospital cardiac arrest

RICHARD BAIN

Background. Survival from in-hospital cardiac arrests remains poor with 14-20% surviving to discharge. Resuscitation guidelines advocate an optimum rescuer posture to deliver chest compressions. Rescuer posture may be influenced by the height of the medical platform during a cardiac arrest. There are no national standards for the height of a medical platform during a cardiac arrest. Currently platform height is determined by the manufacturer. Evidence for the impact of platform height on the quality of resuscitation is limited and conflicting.

Aim. To investigate the effects of platform height on rescuer posture and identify the mechanisms that determine the depth of chest compressions during an in-hospital cardiac arrest.

Method. Forty-three staff trained in Basic Life Support (BLS) were instructed to deliver chest compressions on an instrumented manikin positioned on a medical platform across a range of clinically relevant heights (48-98 cm). Rescuer posture and forces were measured using motion analysis equipment (CODAmotion) and a ground force plate (Kistler, model 9281B). Depth of compression was measured on an instrumented manikin with a chest compliance similar to that of an adult chest.

Results. Platform height determined rescuer posture and was associated with reduced depth of compression at a platform height of ≥68 cm ($P=0.001$). Increasing platform height demonstrated a reduced number of rescuers achieving the depth of compression specified in guidelines. At a platform height of 48 cm, rescuers were able to lean a maximum of 57.6% (SD 10.3) and push a maximum 41.1% (SD 8.2) of their upper body weight against the manikin. At the lowest platform height (48 cm) there was no significant difference between the depth of chest compression achieved through static leaning/pushing and that achieved when dynamically simulating chest compressions (P=0.9). Posture increasingly deviated from the recommended position as platform height increased, and was associated with a reduction in the static force developed through leaning and pushing but increased the dynamic component of chest compression.

Conclusion. Platforms that are too high adversely affect the rescuer's ability to achieve the recommended depth of compression. Platform height influences rescuer posture and determines the relative contribution of the forces delivered using rescuer body weight. Increased dynamic effort is required to compensate for suboptimal posture. Further guidance on positioning medical platforms during an in-hospital cardiac arrest is needed in order to maximise application of rescuers' physical attributes for the delivery of optimal BLS. Resuscitation guidelines and British standards for medical platforms must be aligned.

Table of Contents

List of Tables

List of Figures

DECLARATION OF AUTHORSHIP

I, Richard Bain, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

An investigation of mechanisms determining depth of chest compression during in-hospital cardiac arrest

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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The late John Lester – whose mechanical wisdom was so vital during the development of the mechanical aspect of the resuscitation manikin.

Professor Cathy Bowen – for feedback and comments on the thesis.

Definitions and Abbreviations

2D – two dimensional

3D – three dimensional

ALS – Advanced Life Support

ATP – Adenosine Triphosphate

BLS – Basic Life Support

BMI – Body Mass Index

BPM – Beats per Minute

BS – British Standards

CO – Cardiac Output

CoSTR – Consensus on Science with Treatment Recommendations

CPR – Cardiopulmonary Resuscitation

CPP – Coronary Perfusion Pressure

CODA - Cartesian Optoelectronic Dynamic Anthropometer

DoC – Depth of Compression

FPT – Fitting Person to Task

FTP – Fitting Task to Person

ILCOR – International Liaison Committee on Resuscitation

INACSL – International Nursing Association for Clinical Simulation and Learning

IHCA – In-hospital Cardiac Arrest

NHS – National Health Service

p - probability

RAB – Rescuer Angle Back

RAA – Rescuer Angle Arms

RC (UK) - Resuscitation Council (United Kingdom)

RCT - Randomised Controlled Trial

QALY – Quality Adjusted Life Year

ROSC – Return of spontaneous circulation

SD – Standard Deviation

SEM – Standard Error Mean

SV – Stroke Volume

UK - United Kingdom

1 Introduction

Coronary heart disease, a Western epidemic, is responsible for more deaths than any other disease, is expanding globally[1-3] and therefore a public health problem. Annually, over 275,000 deaths in Europe[4] are attributed to cardiac arrests and in excess of 460,000 deaths are reported within the United States[1]. Cardiac arrests occur with little or no warning but change people's lives forever. Without immediate effective treatment death is inevitable[5,6]. With treatment, the chances of survival increase[5,7].

Patients experiencing an out of hospital cardiac arrest, survival is between 3 and 10%[1,8]. This indicates a greater loss of life than those patients suffering cardiac arrest within the hospital environment, where survival to discharge is approximately 14-20%[1,9-12]. However, this does not exclude survivors living with disability and neurological consequences[13-15]. The economic impact of in-hospital cardiac arrests involves the loss of productivity due to lives lost and health service resources[12].

Those patients experiencing an in-hospital cardiac arrest incur two additional costs[16]. Firstly, the effort to resuscitate the patient, second the cost of the extended hospital stay, potentially in an intensive unit, but may still die, and those that survive to hospital discharge. Survivors of an in-hospital cardiac arrest would access additional health resources i.e. readmissions, as a consequence of the arrest[8] and but could have a reduced quality adjusted life year (QALY) and a consequent reduced contribution to society. However, a quantifiable impact of in-hospital cardiac arrests is difficult to ascertain due to limited or weak evidence[8,16,17].

International[18,19] and national guidelines[20] collaboratively determine cardiopulmonary resuscitation (CPR) as best practice for a cardiac arrest. The fundamental infrastructure of CPR has been presented as the chain of survival (Figure 1-1)[21] since 1991. The chain illustrates the need for rapid structured intervention to optimise survival and maximise quality of life[22]. The second link in the chain demonstrates the role of a rescuer performing chest compressions to enhance the effectiveness of more advanced life saving techniques.

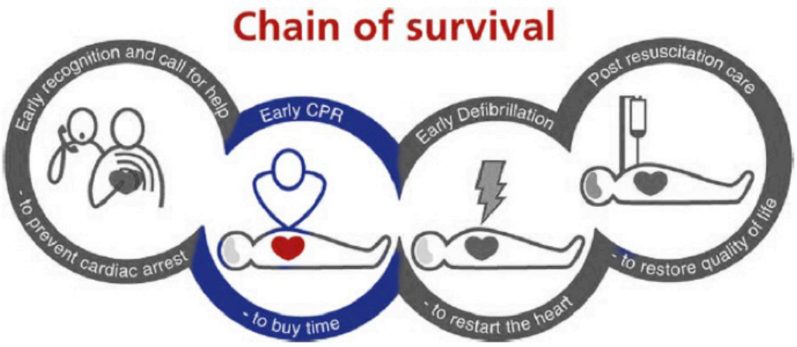


Figure 1-1 Chain of Survival highlighting the early CPR link modified by the author. Image reproduced with permission, Elsevier.

Regular updates to resuscitation guidelines over the last ten years have reported marginal increases in survival rates following an in-hospital cardiac arrest[1,9,23-27]. All links in the chain of survival need to be optimised for survival to be maximised. Fundamentally, an in-hospital cardiac arrest is comprised of: a patient, a clinical environment and rescuer. Three potentially linked factors could impact on the efficacy of chest compressions to provide a transient circulation to sustain life. This research considers the factors in the second link in the chain of survival for an in-hospital cardiac arrest.

1.1 Resuscitation

1.1.1 Resuscitation Physiology

A cardiac arrest is the cessation of electrical and mechanical activity of the heart. Chest compressions determine resuscitation physiology[2,26,28-32]. The initiation of chest compressions generate a transient pressure gradient between the thoracic aorta and right atrium, establishing the coronary perfusion pressure[2] (CPP) (Figure 1-2). In addition, chest compressions create a pressure gradient between the carotid artery and the inter-cranial artery (cerebral perfusion pressure). The coronary and cerebral perfusion pressures cause blood flow to vital organs and assist in maintaining cellular function[28].

During chest compressions, blood flow to the heart occurs during the decompression phase[29,33]. This phase of the intervention is haemodynamically significant as the myocardium receives oxygenated blood via the coronary arteries during diastole. During the decompression phase, the chest recoils and permits coronary blood flow and the left ventricle to refill. In contrast, to the heart, cerebral perfusion is maintained during the compression and decompression phase.

The creation and establishment of the CPP is not instantaneous despite initiation of chest compressions[34,35]. Kern et al[34] reported, between 5 - 10 effective chest compressions are required to create a perfusion pressure (Figure 1-2). This number of chest compressions is approximately one third of the total number delivered during the cycle[18,36]. However, the study assumed the 5 - 10 chest compressions are effective in achieving the required depth of compression. Ineffective chest compressions will prevent or delay an adequate CPP being achieved and lower the chances of survival.

In contrast to the gradual increase in CPP, cessation or interruptions to chest compressions during rescue breathing, pulse checks, rotation of rescuers and defibrillation, results in an almost immediate fall in the transient pressure gradient (Figure 1-2). As such, blood flow to vital organs is compromised and another 5 - 10 effective compressions are necessary to maintain adequate perfusion.

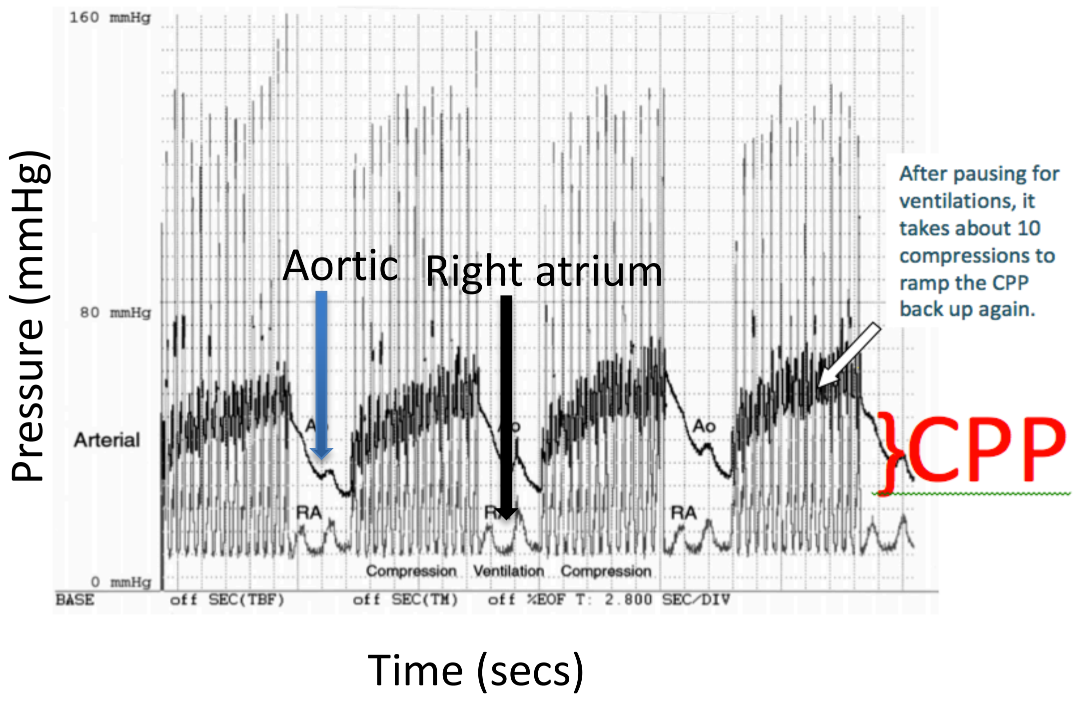


Figure 1-2 A graph demonstrating an aortic and right atrial pressure with respect to time. The difference in pressure determines the coronary perfusion pressure (CPP)[30]. It takes approximately 10 compressions to reached an effective CPP. (modified by the author). Image reproduced with permission, Elsevier.

Effectiveness of chest compressions and survival are determined by the depth of compression, which according to Babbs et al[37] and others [29,31,38,39] is directly related to the volume of blood ejected from the heart per compression i.e. stroke volume. Furthermore, effective chest compressions deliver approximately 20 - 30% of a normal cardiac output (5 L/min - adult)[36,40].

Therefore, the maximum transient cardiac output during resuscitation is approximately 1 - 1.5 L/min. The reduced, but critical cardiac output could determine the difference between life and death and is determined by the quality of chest compressions[29,37].

It is acknowledged that resuscitation physiology studies are based on animal populations, with evident thoracic anatomical differences to humans[29,38,41,42] limiting the translational impact to human victims. Human research is limited to a number of small observational studies[43-47].

1.1.2 Resuscitation – Time since Cardiac Arrest

Survival from a cardiac arrest is determined by the quality and timing of life saving treatment[10,48-50]. Research into resuscitation highlights three phases of a cardiac arrest[51] from the onset of ventricular fibrillation; electrical phase lasting up to 4 minutes, mechanical phase between 4-10 minutes and the metabolic phase, in excess of 10 minutes (Figure 1-3). These timings are assuming the cardiac arrest is in hospital and has been witnessed by electrical monitoring.

Electrical Phase	Mechanical Phase	Metabolic Phase
(0-4 mins)	(4-10 mins)	>10 mins

Figure 1-3 Three phases of a cardiac arrest[51]

If the patient is in VF or VT, resuscitation guidelines advocate immediate defibrillation, during the electrical phase, to optimise the successful establishment of a heart rhythm compatible with life. Cobb et al[52], Gilmore et al[49] and Ristagno et al[39], noted, any arrest, in excess of 4 minutes; victims should receive effective chest compressions prior to electrical defibrillation. Physiologically, this action would refill the volume depleted left ventricle, re-establish a coronary perfusion pressure and delay metabolic deficiencies[48,49]. Ristagno et al[39] and others[53,54] suggested chest compressions should take precedence over electrical defibrillation, reiterating the importance of effective chest compressions.

1.1.3 Resuscitation Methodology

Resuscitation guidelines provide instructions to rescuers to deliver effective chest compressions. Rescuers are advised to compress the patient's chest to generate the CPP (section 1.1) (Figure 1-4, left). Resuscitation methodology demonstrates a rescuer positioned adjacent to the victim (Figure 1-4, right) with the rescuer's shoulders positioned over the centre of the patient's chest. Rescuer posture is intended to create and deliver a force to overcome resistance and compress the victim's chest[55]. In this posture, the rescuer's the hips act as a fulcrum and the upper body provides the effort to compress the chest and acts as a 3rd class lever.

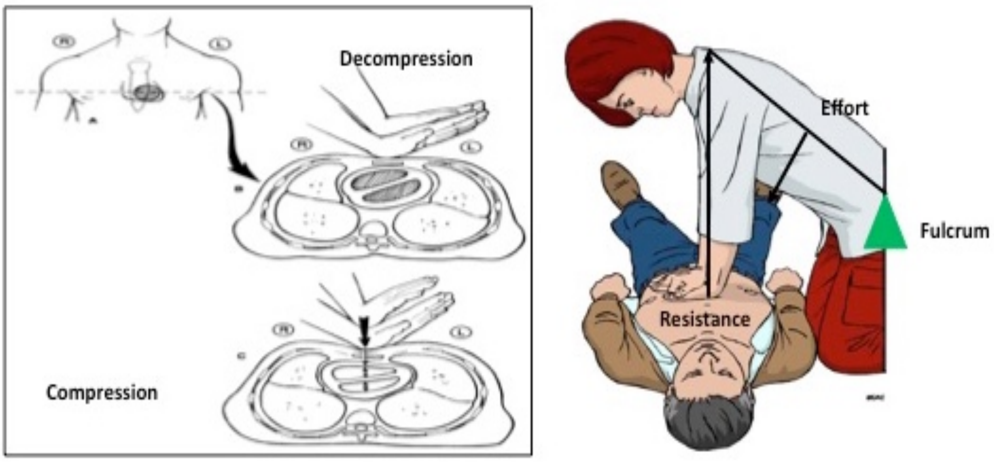


Figure 1-4 Schematic demonstrating chest compression and decompression adapted from Nolan (left) and the recommended posture for delivering chest compressions (right). Modified by the author to demonstrate the 3rd class lever system of the upper body[20]. Image reproduced with permission, Elsevier.

1.1.4 Guidelines - Depth of compression

The International Liaison Committee on Resuscitation (ILCOR) are responsible for reviewing and evaluating research on resuscitation and to publish ILCOR Consensus on Resuscitation Science (CoSTR)[56]. The purpose of the guidelines is to improve survival following an in-hospital cardiac arrest and reduce variations in survival. The development of guidelines is determined by three factors, science, education and implementation. However, despite science being a factor it is acknowledged that robust randomised controlled trials in resuscitation are limited[57]. Therefore, guidelines have been founded on observational or animal studies.

Despite the weak evidence base, during the time of these investigation the guidelines changed as follows. In 2005 resuscitation guidelines[19] required rescuers to compress the victim's chest to a depth of 40-50 mm at a rate of 100 beats per minute (BPM). These guidelines are applicable for the first experiment (**chapter 3**). The updated 2010 and 2015 resuscitation guidelines[20] instructed rescuers to deliver chest compressions to a depth of 50-60 mm at a rate of 100-120 bpm. These guidelines are applicable to the second experiment (**chapter 4**). The ratio of chest compressions to rescue breathing did not change during these reviews and remained at 30:2.

1.1.5 Determinants of Successful Resuscitation

Despite regular changes to resuscitation guidelines[18,19,58], survival rates from in-hospital cardiac arrests demonstrated marginal improvement[1,39,59-62]. Studies highlight determinants of poor outcomes related to rescue attempts (Table 1)[30]. More specifically, problems and comments related to the quality of BLS and included: poor depth of compression[63,64], residual chest compression depth, slow rates of compression, high ventilation rates, delayed and/or interruptions to chest compressions, as well as location within the hospital and timing of the arrest[1,65-67 68 26].

Table 1 Determinants of Successful Resuscitation[30]

Duration of cardiac arrest
Aetiology of cardiac arrest
Co-morbidity
Early intervention
Quality of BLS

Inadequate depth of compression was highlighted as the most frequent deficit and reduced the chances of patient survival[39,69,70]. Poor depth of chest compression could indicate inadequate training, poor retention of BLS skills[71] or poor technique created by the resuscitation environment. The small, but critical transient cardiac output could be vulnerable to sub optimal chest compressions.

1.2 Resuscitation Environments

Resuscitation can present rescuers with difficult or special resuscitation environments[21,72]. Special environments typically focus on specific locations in and out of hospital. In hospital environments can include theatres, cardiac catheter laboratory[21], whilst outside the hospital can include the aquatic environment i.e. drowning[36] or airplanes or trains associated with confined spaces[73-75]. The physical aspects of these environments could prevent the rescuer from achieving the recommended rescuer posture (Figure 1-4) to perform chest compressions[18,55,76]. Therefore it is proposed within this thesis that sub-optimal environment could inadvertently occur within the hospital environment not previously mentioned i.e. on hospital wards.

During an in hospital cardiac arrest, chest compressions must be delivered to sustain life and there are three fundamental factors are present 1. Patient 2. Rescuer 3. Medical Platform (Figure 1-5). A mismatch of these factors could determine the effectiveness of resuscitation efforts during an in-hospital cardiac arrest.

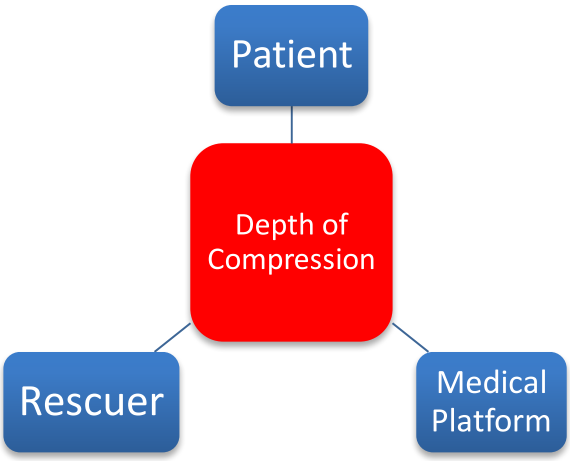


Figure 1-5 Key factors related to the depth of compression.

Patient - The patient could be young or old and have unique physical attributes i.e. compliance of the patient's chest, providing resistance to rescuer effort. Tomlinson et al[77] and others[78,79] noted the curvilinear characteristics and variability in adult human chest compliance. However, during a cardiac arrest the adult patient chest compliance is predetermined and unmodifiable.

Rescuer - The cardiac arrest team is comprised of a group of healthcare professionals, trained as rescuers, with potentially a range of rescuer attributes i.e. height and weight, and experience. Application of resuscitation guidelines advocate the rotation, every two minutes, of rescuers during the arrest to prevent rescuer fatigue and maintain quality of resuscitation efforts[18,36,58]. However, rotation of the rescuers potentially alters rescuer attributes[80].

Medical Platform - A medical platform is the dominant environment for the delivery of chest compressions within the in-hospital environment. The compliance[81,82] and height of the medical platform[81,83-91] could inadvertently create a special environment during an in-hospital cardiac arrest. National Health Service (NHS) hospitals employ a multitude of platforms on which patients are treated[92-94]. The variety of platforms present within hospitals create a range of heights the platform could be positioned during a cardiac arrest.

Theoretically, the height of the platform and the height of the rescuer[76] could determine rescuer posture i.e. rescuer shoulders over centre of chest (figure 1.4). Which could ultimately determine the efficacy of the rescuer to perform effective chest compressions. A review of existing research into platform heights and identification of platforms used within the NHS is required.

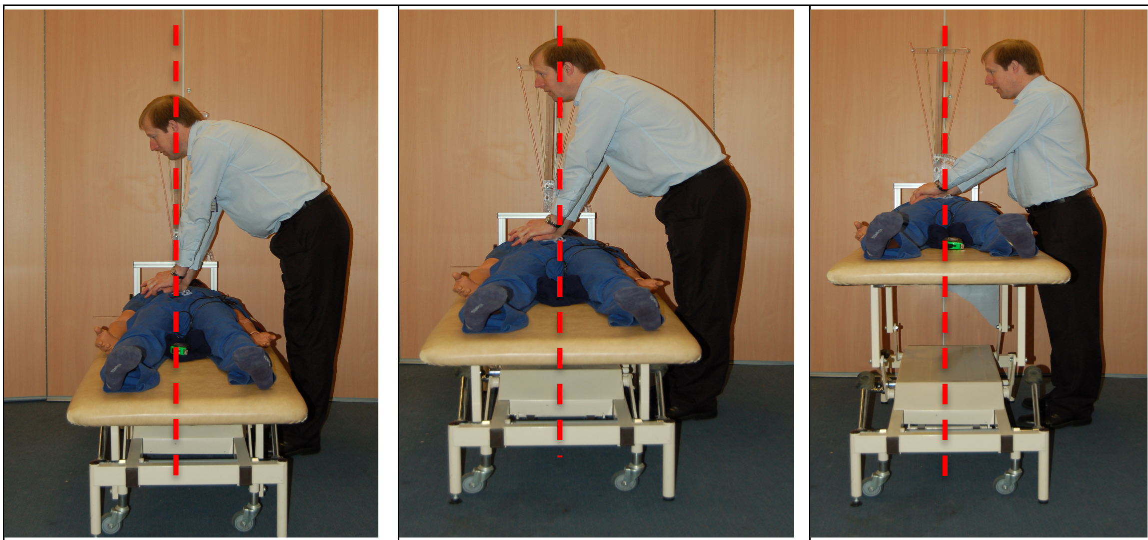
1.3 The Rescuer

Repeated compression of a patient's chest to the minimum depth requires the rescuer to generate and deliver a force. During BLS, a rescuer is equipped with inherent physical attributes of height and weight. Both attributes could affect the efficacy of chest compressions. Rescuer height may influence posture, whilst rescuer weight encompasses rescuer mass and muscle groups. Collectively these attributes produce momentum to create force. It is unclear which of those attributes dominate the creation and delivery of the required force, or if they could be rendered as ineffective from poor posture.

The described rescuer posture (Figure 1-4) utilises the rescuer's upper body as a 3rd class lever with rescuer hips acting as a fulcrum[95,96] and resistance distal to the fulcrum, and effort in between (Figure 1-4). The mass of the upper body, assisted by gravity, provides a vertical force, conducted by the rescuer's arms, to the victim's chest. Antagonistic muscle groups provide the repeated contraction and relaxation of the rescuer's upper body, and provide momentum to the rescuer's upper body mass.

However, it is unclear which of the attributes identified, are being utilised effectively or the contribution of each attribute. The contribution and distribution of forces identified could be altered by posture and rescuer attributes[97]. Poor rescuer posture could influence the contribution of rescuer forces and degrade the effectiveness of chest compressions.

In addition, it is proposed rescuer posture in relation to a patient during an in-hospital cardiac arrest can be predicted. During a resuscitation attempt, a rescuer is positioned adjacent to the victim[18-20,58]. The rescuer positions their hands on the centre of the victim's sternum[18,36,58]; rescuer's feet are typically flat on the floor, the upper body pivots at the hips. Photographic evidence demonstrates a rescuer in three different postures related to the height of the platform (Figure 1-6).



a) Low height	**b)** Mid height	**c)** High height

Figure 1-6 A rescuer positioned adjacent to a manikin demonstrating altered posture due to a range of platform heights (a, low, b, mid and c, high). Midline of the manikin is represented by a red dashed line.

The photographic evidence above demonstrates a rescuer changing posture at three different platform heights. At the lowest platform height (a), rescuer posture marginally complies with resuscitation guidelines[18,36] i.e. with the rescuer's shoulders positioned over the centre of the manikin's chest and arms in a vertical plane. At the mid platform height (b), rescuer posture has changed; the rescuer's shoulders are displaced from the mid-line (red dashed line) of the manikin and the rescuer's back has become more vertical. At the tallest platform height (c), the rescuer is in a vertical posture and the arms have become more horizontal in relation to the manikin, deviating further from recommended posture documented in the resuscitation guidelines[18,36,55,98]. It is proposed rescuer posture can be predicted for a range of platform heights using a simple geometrical model. This will help to understand the mechanisms related to changing platform height during an in hospital cardiac arrest.

1.3.1 Rescuer Ergonomics of Chest Compressions

Rescuers are tasked with generating and delivering forces, described above, to compress the patient's chest to the required depth[18,20,58]. Rescuers have mass, muscular groups and momentum to create and deliver force. The depth of compression achieved during BLS is proportional to the force applied to the patient's chest, and influenced by the compliance of the victim's chest[77,79].

The orientation of rescuer body segments, caused by the geometrical relationship between the rescuer and patient, determines the working posture for the practical task of resuscitation. Task posture is limited by the connections between the rescuer and the dimensions of the workspace [99,100] i.e. medical platform. The work output of an individual is the greatest force that can be achieved in the given workspace[96]. To optimise the efficiency of the working posture, the degree of effort should be minimised to maximise the task output. Furthermore, the efficiency of the working posture will determine the sustainability of the work being performed and therefore limit the effects of fatigue or injury.

Inherent rescuer biomechanical factors determine the limitations of the forces obtainable by the individual, these limitations include[99] muscular, gravitational and Interfaces

Muscles - The rescuer's upper body is comprised of muscles and bones, and has mass. Bones articulate at joints[101], muscles are attached to bones[102]. The contraction of a muscle across a joint creates movement of the bone, including the mass of the body segment, distal to the joint. The parameters determining efficiency and strength of a muscle contraction is multifactorial; but includes muscle orientation, type, muscle tension and configuration [95,103].

Gravity – The movement of bodily segments is achieved with anatomical levers and functional torque[104]. In addition to muscles being used to create movement, inertia of body segments can be exploited as a mass and the acceleration of mass due to gravity ($9.81 m/s^2$). The contribution of gravitational forces converts body mass into weight and produces a vertical force.

Interface - The force generated by the rescuer i.e. gravitational and muscular, interfaces with the patient's chest via the rescuer's arms. The point and angle of application at the interface is determined by rescuer posture and could present limitations[96]. The optimum interface for chest compressions is in the vertical plane. Changes to the point of application would result in reduced vertical forces and the creation of horizontal forces.

1.4 The Patient

Rescuer forces have to overcome the resistance of the patient's chest compliance to achieve compression. Human studies into determining chest compliance are limited[77,79,105], but revealed a curvilinear characteristic. Tomlinson et al[77] reviewed the chest compliance of 90 adult chests (Figure 1-7) and demonstrated a force-depth relationship of 6.4 N/mm – 7.7 N/mm. Furthermore, Tsilik et al[79] also established the adult human chest characteristics as between 6.2 N/mm – 8.8 N/mm. However, the majority of resuscitation training manikins are typically fitted with compression springs, which present a linear force-depth relationship. To achieve the required depth of compression (40 mm) a force of 300 N is required. Therefore, a manikin with a chest compliance similar is required.

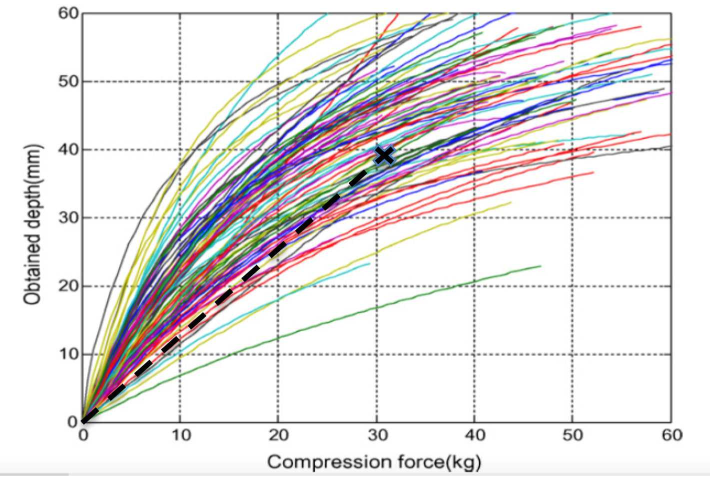


Figure 1-7 Line graph demonstrating the Adult human chest characteristics[77] and median force required to compress a chest to 40 mm. Image reproduced with permission, Elsevier.

1.5 The Clinical Environment

1.5.1 Medical Platforms

The range of platform heights for the research must reflect the range of heights that could be encountered clinically. The range of heights will be determined by identification of the platforms that patients typically experience an in-hospital cardiac arrest.

1.5.2 In-Hospital Cardiac Arrest

The first National (UK) figures for in-hospital adult cardiac arrests revealed over 22,000 cases reported from 144 acute NHS trusts from April 2012 until September 2013[10,106]. More recently, the number of hospitals participating in the audit increased to 188[107]. However, the national dataset did not reveal the areas within the hospitals that cardiac arrests occurred i.e. inpatients, outpatients or other areas. Therefore, the author audited in-hospital cardiac arrests in a local acute NHS hospital to identify the make and models of medical beds used within NHS trusts.

1.5.2.1 In-hospital Cardiac arrest and medical platform – Audit

Background to audit

The author accessed cardiac arrest data from a large acute NHS trust for 2009 and 2010 (UHS). A review of the resuscitation audit data demonstrated the majority of cardiac arrests within the trust over 2 years (97%) occurred on hospital wards[108]. As such, it was assumed that medical beds are the primary location for in-hospital resuscitation.

Aim of audit

To determine the type of medical beds used within NHS trusts. Identify the range of heights of those platforms, including any CPR facility.

Results of audit

The author identified the trust's primary supplier of medical beds was ArjoHuntleigh™ and a smaller selection of other medical platform providers (table 2). The model specifications, including height range and CPRT facility, of ArjoHuntleigh beds were accessed via company representatives[109] and audit (table 2). The distribution of different ArjoHuntleigh medical beds for the trust are presented in table 4.

However, resuscitation audit data did not reveal the platform/bed the patient had arrested on within the hospital setting i.e. a trolley, stretcher etc or on the floor. Therefore, it is unclear if all in-hospital arrests occurred on a medical bed within 1 trust. In addition, the distribution of the various manufacturers and models of medical beds within the trust is unclear. Furthermore, discussions with the resuscitation team revealed patients experiencing a cardiac arrest within Intensive care units do not alert the arrest team due to acute services provided within those units. The medical platforms of these specialist units is unknown. Despite the limitations of the medical platform audit, the results do provide guidance for the range of heights required for the thesis (chapter 2). Furthermore, irrespective of the manufacturer, all medical platforms must conform to a national standard.

1.5.3 Medical Platforms - Standards

Manufacturers of medical platforms must comply with British Standards 60601-2-52-2010 (BB3.2)[93], which dictate safety standards and specifications of medical platforms. The range of heights a medical bed must operate between is 400 – 800 mm. The height range does not include the height of the mattress. Mattress heights vary with different manufacturers[92,94]. Furthermore, British standards do not state a height at which the platform should be positioned for a cardiac arrest.

Manufacturers of medical beds must conform to British Standards but have intrinsic features, including a CPR facility for resuscitation (Table 2) (

Figure 1-7). Once activated, the platform adjusts to a horizontal position and a specific height. However, the resuscitation height setting varies between manufacturers, and between different models from the same manufacturer. The low and high height values include a mattress (standard mattress 150 mm). Therefore, to be inclusive of all clinically relevant heights, a range of 480 to 980 mm will be used in the method section of this thesis.

Table 2. Summary of Medical Platforms

Manufacturer	**Model**	**Low Height (mm)**	**CPR (mm)**	**High Height (mm)**
Arjohuntleigh™	480/460	590	750	990
	560/880	560	720	960
	Kingsfund	600	N/A	970
Sidhil™	Innov8	552	*No setting	952
Hill-Rom™	AvantGuard 1200	500	Horizontal	900
	900	495	Horizontal	880

*When the CPR function is activated, the bed lowers to 400 mm and then raises until the function is released.

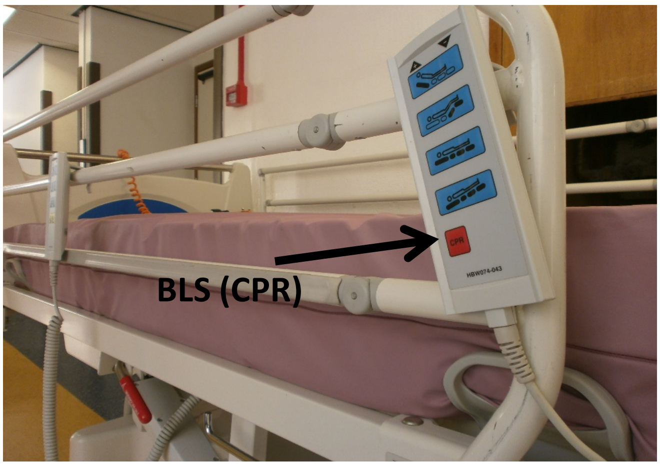


Figure 1-7 A medical platform (ArjoHuntleigh™) demonstrating the BLS (CPR) function.

1.6 Evidence Base of Medical Platforms and Chest Compressions

This section critiques the current literature on the effects of platform height on the quality of chest compressions. To ensure all relevant literature has been included the search strategy employed the PRISMA methodology, and included key terms and search functions to capture existing studies (appendix D). The DELPhis search, encompassed Medline, CINHAL, Sciencedirect, Cochrane Database, identified 660 articles related to resuscitation and chest compressions. Post screening 549 articles remained and 410 were eligible and abstracts accessed. From eligible group 7 studies were identified as directly related to platform height and chest compressions (table 3). The 7 studies were retrieved in full text and encompassed 257 subjects and presented different methodologies to investigate the effects of platform height on the depth of compression.

Literature Review

Perkins et al [81] reported, using an RCT, platform height did not impact on the quality of chest compressions using 20 2nd year medical students BLS instructors. The methodology employed a relative rescuer mid-thigh height and a low BLS (CPR) platform height to compare the depth of chest compressions. However, the study did not reveal the height setting, for the low fixed BLS position or the make/model of the platform used for the study. It is difficult to interpret any differences in depth of compression in the context of platform height without a known height. Furthermore, the mean height of the rescuer population was not presented which limited the translation of the relative aspect of this work into clinical practice. Lack of clarity within the methodology introduces uncertainty in the comparative nature of the results.

In addition, Perkins et al[81] included mattress compliance as a variable, more importantly an unknown variable. Although compliance was a constant, it is unclear if the mattress is comparable with mattresses purchased by the NHS. The impact of mattress compliance has been considered by various authors[110-112]. Therefore, mattress compliance may have influenced the results and prevented differences in compression depths to be detected.

However, Perkins et al[81] did acknowledge the importance of positioning the rescuer's shoulders above the victim's in accordance with resuscitation guidelines. This postural issue was also raised by Handley et al[74] who investigated, resuscitation in special circumstances and indicated force delivered by the rescuer is inversely related to platform height.

Chih et al[83] agreed with Perkins et al[81] despite employing a different methodology. Chih et al[83] investigated the effect of medical platform heights, predominately focusing on the kinematics (angle of movement) and rescuer workload but also commented on the quality of chest compressions with 18 healthcare providers. Chih et al[83] explored three different, absolute heights that included floor (rescuer kneeling), low (37 cm) and high (63 cm) using a non-compliant surface.

Chih et al[83] did not report a difference in the depth of chest compressions at different heights (floor 43.5 mm, low 42.0 mm and high 44.0 mm). However, it is unclear as to the rationale for the platform heights used and therefore limits the translational value to clinical practice. Except the platform heights were regarded by Chih et al[83] as being above and below the rescue population's knee height (average rescuer height 165 cm). The magnitude of the difference above and below the rescuers knee height was not presented. Therefore, the study has to be considered as using absolute platform heights.

Oh et al[91] also reported no significant differences in the quality of chest compressions performed on the floor or kneeling on a non-compliant platform: using a 20 4th year medical students (mean height 170.4 cm SD 7.3 cm). However, the platform height was set to the relative height of each rescuer's knee. Therefore, there was no difference in height between these two positions (floor and knee height). The study did not detect a difference in the depth of compression delivered. The study did control variables and commented on the platform surface being plywood blocks to recreate the arrest scenario. Finally, the study did not investigate a range of platform heights that could be encountered clinically. As such, translation of results into clinical practice is limited.

In contrast to the previous studies, other authors[84,86,88,89] reported platform height does impact on the quality of chest compressions. Again, these studies have revealed varying methodologies to examine the effects of platform height on depth of compression. These are discussed below;

Jones et al[88] predominately observed the spinal kinetics and energy consumption of the rescuers in different rescuer postures. Nonetheless the paper commented on the reduced quality of chest compressions related to platform height. Fifty-six rescuers comprised of nurses and emergency technicians were instructed to perform chest compressions in a kneeling position and standing at a platform height of 63.5 cm. It is unclear from the paper as to the rationale or any reference to resuscitation guidelines or platform standards for a platform height of 63.5 cm. Furthermore, the methodology allowed rescuers to stand on 20 cm wooden blocks if they considered the platform height of 63.5 cm was too high. It is also unclear from the data how many rescuers selected this option. Jones et al[88] observed altered rescuer posture influencing muscle expenditure, which may have impacted, on the overall quality of chest compressions. Jones et al[88] proposed the difference in muscular contractions are influenced by the posture of the trunk, and comments that standing during the delivery of chest compression is less favourable than kneeling.

Cho et al[84] investigated the effects of platform height with 24 healthcare professionals and used heights relative to the rescuer. These heights were 10 and 20 cm below and above the rescuers knee height and were considered to be superior surface of the bed. Cho et al[84] reported knee height as the optimal height for performing chest compressions with reduced depths of compression above and below the rescuer's knee. However, the height of the rescuer's knee (46 cm SD 3.0) would suggest the range of absolute platform heights encountered, for 98% of the population, were potentially 20 cm to 72 cm. The potential range of heights did not consider the range of heights a medical platform could be positioned. The study heights were randomised and performed on a non-compliant surface. However, one of the inclusion criteria for the rescue population was BLS training within the previous 2 years. This period of time exceeds the current UK resuscitation guidelines[18,20,36] and could introduce another variable related to skills retention.

Lewinsohn et al[89] examined platform height relative to the rescuer using a wider more diverse range of rescuers (n=101), including doctors, nurses, physiotherapists and students. The study used an unidentified theatre trolley and not a medical bed. The protocol included relative rescuer heights; mid-thigh, anterior superior iliac spine and xiphisternum. The paper did not reveal the order or randomisation of the three heights. The heights employed were the height of the manikin's chest and not the trolley height. The mid-thigh height was identified as the most effective height for chest compressions; although the study did not reveal the demographic data of the cohort.

The translation of the Lewinsohn et al results into clinical practice is difficult, it is unclear as to the type of trolley, height range of the device or the heights of the rescuers. A unique component of this paper was the physiological approach to determining the quality of resuscitation. The methodology included a modelled intrathoracic pressure and not a compression spring, creating difficulty in comparing outcomes.

Hong et al[86] conducted research into rescuer posture for in-hospital cardiac arrest, using one platform height (80 cm) with three different rescuer postures. Thirty-eight rescuers performed chest compressions kneeling on the platform, standing adjacent to the platform and using a step-stool (20 cm). It was reported kneeling and step-stool height both demonstrated a greater depth of compression than the standing position, and subsequently advocated kneeling on the platform or employing a step- stool as the optimum posture for delivering chest compressions in a hospital environment.

It is unclear from Hong et al[86], as to the rationale for one platform height. This limited the translational aspect of the work as medical platforms operate over a range of heights. The inclusion of the step-stool implies platform height is a contributing factor. There was no justification as to the height of the stool. Considering the potential heights of the rescue population, 154.3 to 187.9 cm, the addition of the stool would increase rescuer height to 174.3 to 207.9 cm. Therefore, it is unclear as to which rescuers would benefit from the step-stool. However, the order of the BLS was randomised and a non-compliant platform surface was employed. The recruitment process included rescuers who had received BLS training within the last 2 years. A similar training issue mentioned earlier.

Edelson et al[85] investigated the impact of a step stool, using 50 volunteers and reported an increase in the mean depth of compression (4 mm) with the use of the step stool (23 cm) during resuscitation . It is unclear as to justification of the height of the stool that differs from the Hong et al[86] study by 3 cm. The improved outcome was directed at rescuers with a physical height of less than 167 cm. The advice was unclear for taller rescuers. Lee at al[113] also reviewed the impact of a step-stool (20 cm) with a fixed platform height (78 cm). This paper did not provide justification for the heights used or why the platform height was fixed at 78 cm, but did comment on the stool assisting with rescuer posture.

Despite previously reporting platform height did not impact on chest compressions[91], more recently Oh et al[90] went further and proposed a kneeling stool, allowing rescuers to kneel adjacent to the patient. This concept would prevent adjustment of platform height during resuscitation. Papers investigating the impact of step or kneeling stools[85,86,90,113] are collectively implicit but consistent in recognising platform height does influence the quality of chest compressions[55].

1.6.1 Consideration of other Resuscitation Variables

1.6.1.1 Kneeling During Chest Compressions

Papers previously mentioned, reported rescuers performed chest compressions whilst kneeling on the platform in accordance with the current guidance[55]. However, caution is required when kneeling on a medical platform during a cardiac arrest. The combined weight of the patient and rescuer must not exceed the safe loading specifications and weight distribution of a particular platform[93]. Furthermore, rescuers could be at an increased risk of injury due to the presence of needles, bodily fluids on the medical platform and impending defibrillation of the patient. The health and safety of rescuers needs consideration if kneeling was to be advocated.

1.6.1.2 Surface Compliance

97% of in-hospital cardiac arrests occur on wards (audit by author), therefore it is assumed patients are positioned on a hospital bed. Audit data did not reveal more specific detail of surface compliance. Medical beds will include a mattress which vary in depth and material depending upon manufacturer and the patient's needs. The effect of mattresses on the quality of chest compressions has been reported by various authors[81,110,112,114]. It is considered that as a patient's chest is compressed the force delivered is conducted through the patient's chest and into the mattress. The compliance of the mattress absorbs the force and attenuates the depth of compression. However, evidence on the use of backboard is still equivocal and has been controlled for this experiment.

1.6.1.3 Summary of Platform Height Literature review

Despite CoSTR changes to resuscitation policies and emphasis on high quality chest compressions, guidance on optimum height of medical platforms-during an in-hospital cardiac arrest, is not evident and it has been suggested to be based upon expert opinion[55,89]. Research has produced conflicting evidence derived from observational studies, employing differing methodologies. A combination of absolute platform height and relative rescuer height as variables, and incomplete demographic data has prevented explicit interpretation and prevented a clear message to resuscitation policy makers. [81,83,84,86,88,89,91]

Previous work (Table 3) into the effects of platform height on the quality of chest compressions has not systematically examined a clinically relevant range of heights or commented on specifications published by British Standards[93]. All studies coded green (Table 3) indicate platform heights that are considered within, but not encompassing, the range of standardised heights. Of those that encompass a range of heights, contrasting results on the effects on depth of compression is evident. In addition, these studies do not consider the CPR function on medical platforms. The CPR height is within the published guidelines but is determined by the platform manufacturer. These studies do not consider rescuer height as a variable that may influence results and impact on those platforms with a CPR function at a specific height. Those studies coded red do not consider the published range of platform heights or are not relevant to the research question.

Despite some studies using platform heights relative to the rescuer, the results of these studies are undermined with varying methodologies and prevent direct clinical translation. The underlying message from the studies demonstrate a change in depth of compression is, a lower platform or a taller rescuer is preferred implying platform height is important. However, to incorporate a relative rescuer height as the marker for optimum platform height[55] does not consider additional aspects of resuscitation policies. As previously mentioned, rescuers are instructed to rotate every two minutes to prevent fatigue. Interruptions to chest compressions are detrimental to the likelihood of survival.

Collectively, previous research has not considered the effects of platform height and rescuer height, across a range of clinically relevant heights, on the depth of compression. Nor have they determined the significance of each parameter.

Table 3 Summary of Platform Height Literature Review

Platform height has effect on the Depth of Compress	No	No	No	Yes	Yes	Yes	Yes
Range of Platform Heights	Low CPR	Floor	Floor	Kneeling on bed	10cm -/+ knee height	Mid-thigh	Kneeling on bed
	Mid-thigh	37 cm	Knee height	Standing (63.5 cm)	20 cm -/+ knee height	Ant sup iliac spine	20 cm (Footstool)
		63 cm				Xiphisternum	80 cm (Standing)
Considered Medical platforms	No	No	No	No	No	No	No
Platform heights Absolute/relative height	Both	Absolute	Relative	NA	Relative	Relative	Both
Platform & Surface	Bed Compliant	Table Non-compliant	Bed Non-compliant	Bed Compliant	Plywood blocks Non-compliant	Theatre trolley Compliant	Bed Non-compliant
Simulation	Manikin	Manikin	Manikin	Manikin	Manikin	Manikin	Manikin
Study design	RCT cross over study	RCT Cross over study	Non RCT single blind, cross over study	3 group non RCT study	RCT, single blinded study	RCT cross over study	RCT, cross over study
Sample size	20	18	20	36	24	101	38
Cohort	BLS Instructors	Medical technician firefighters and emergency nurses	4th year medical students	Nurses and emergency medical technicians	Healthcare providers	Doctors, nurses, physiotherapists and students	Student nurses or paramedics
Measured outcome	DoC	Rescuer Posture	DoC	Rescuer energy	DoC	Intrathoracic pressure	DoC
Year of publication	2006	2008	2013	2008	2009	2012	2014
Author	Perkins[81]	Chih[83]	Oh[91]	Jones[88]	Cho[84]	Lewinsohn[89]	Hong[86]

Legend:
Green – clinically relevant platform heights demonstrating a difference in depth of compression.
Red – not clinically relevant, no difference.
Amber not applicable.
DoC – depth of compression

1.7 Evidence Base of Geometrical and Biomechanical aspects of Resuscitation

Research examining the effects of platform height on the quality of chest compressions, do not always primarily consider the geometrical and biomechanical aspects of delivering life-saving treatment[83,84,89 81]. In contrast, the biomechanical orientated papers[115,116] focus primarily on the kinematics (angles)[116] or kinetics (forces)[115], associated with spinal injuries or rescuer fatigue and are not explicitly inclusive of the quality of chest compressions[115,117]. The literature search previously mentioned identified 7 studies, 2 of which were related to biomechanics of resuscitation.

Jones et al[88] and Chih et al[83] investigated the biomechanical aspects of chest compressions and published contrasting results on the quality of chest compressions associated with altered rescuer posture, determined primarily by non-standardised platform heights.

Chih et al[83] investigated the kinematic, kinetic and rescuer physiology of chest compressions for 3 different rescuer postures with 18 rescuers. They reported no effect on the depth of compression for different platform heights. Although the study did observe the position of the rescuer's hips and shoulders was determined by platform height. The mean hip angle for chest compressions delivered, whilst kneeling on the floor, was -47.4° (SD 4.3) and -42.5 (SD 4.7) at the lower platform height (37 cm). Demonstrating similar rescuer postures between the two lower rescuer positions. At the higher platform height (63 cm), hip angle had decreased to -16.2° (SD 3.3), suggesting a more vertical posture for the rescue population.

In addition, the position of the rescuer's shoulders demonstrated a similar but not identical pattern to the hips. The mean shoulder angle for the floor was -54.5° (SD 1.2), low height -61.7 (SD 2.1) and tallest height -38.5° (SD 1.5). It is unclear regarding the increased shoulder flexion at the low platform height compared to the floor. However, the tallest platform height did demonstrate reduced shoulder flexion suggesting the rescuer is in a more upright posture at the tall platform height. Despite not detecting changes in force/depth of compression, Chih's et al[83] confirmed rescuer kinematics are associated with platform height.

Recording kinematic changes in the rescuer population at different platform heights, Chih et al[83] reported a minor change (6 N) in forces detected by an axial transducer fixed to the manikin's chest. However, the paper did not justify the range of heights used for the study or blinded the rescuers to the different heights. The increase in shoulder flexion at the low height highlights the issue of not sampling at more frequent platform heights.

The change in force manifested in a marginal and expected change in depth of compression between the three different platform heights. Nonetheless, the compression force dataset presented by Chih et al[83] demonstrated a wider degree of variability, amongst rescuers, at the highest platform height. This could suggest the maximum and minimum values could have influenced the mean compression force value and masked differences between alternate platform heights that were not investigated. The paper did not reveal the chest compliance of the manikin or comment on the effect, if any, of a transducer on chest compliance of the manikin.

In contrast, Jones et al[88] focusing on the kinetic and rescuer physiology aspect of resuscitation, reported platform height did alter rescuer posture, rescuer power, oxygen consumption and commented on the effects of the efficacy of chest compressions. Interestingly, Jones also commented on a compromised posture, which would be interpreted as special circumstances.

The study observed forces derived from motion detection sensors, ground force plate and anthropometric data for two different rescuer postures determined by platform height. During a kneeling position rescuer's shoulders vertically above the manikin's chest, less spinal activity was recorded. In contrast, the standing position revealed more spinal activity. Jones et al[88] hypothesised as to the underlying mechanism behind the results, as being related to rescuer posture.

Furthermore, the rescuer's kneeling position created a more horizontal trunk and therefore engaged trunk extension muscles. Where the standing position, Jones et al[88] reported the trunk as more vertical and required flexion muscles to create power. The markers used for this kinematic study focused on spinal activity and did not include additional body segments.

Platform height of 63.5 cm was not rationalised and rescuers experiencing difficulties performing chest compressions in the standing position, were provided with 20 cm wooden blocks. Additional work in this area included Jones et al primarily investigating issues related to back pain/injury and rescuer fatigue[88,116-119].

Jones et al[88] also commented the physiological effects on the rescuer during kneeling and standing posture. Rescuers in a standing posture required more energy but consumed less oxygen. Interestingly, the height of the rescuer influenced the oxygen consumption. Taller rescuers consumed less oxygen than shorter rescuers. The male rescuers were taller than female rescuers and demonstrated a higher percentage of effective compressions.

1.7.1 Biomechanics Literature Summary

Existing literature into the biomechanics of chest compressions is limited despite the significance of a cardiac arrest and the 60 years it has been a practical task performed by healthcare professionals. Previous research into the kinematic and kinetic aspects of chest compressions at different platform heights have demonstrated altered rescuer posture. The altered rescuer posture was determined by the height of the platform surface. However, the studies cannot provide clarity or reproducibility of chest compression data. Both studies failed to justify the range of heights used and make no reference to clinical platforms during an in hospital cardiac arrest, nor offer a theoretical concept for rescuer forces.

1.8 Summary of Chapter 1

Existing simulation studies on resuscitation and platform height presented conflicting evidence resulting in an unclear message to potential rescuers and ILCOR.

Key resuscitation factors have been identified as rescuer, patient and medical platforms. Patients have a chest compliance which must be overcome by the rescuer to compress the chest and sustain a transient circulation. Patients in NHS hospitals are positioned on medical platforms that must conform to British standards. Resuscitation guidelines advocate a rescuer posture of their shoulders over the centre of the patient's chest. However, preliminary investigations have revealed rescuer posture changes with rescuer and platform height, potentially preventing the recommended posture being achieved.

Poor rescuer posture, due to inappropriate platform height, has been discussed as having a functional consequence. In the recommended posture the rescuer upper body acts as a moment. The weight of the rescuer, with gravity, is transferred to the patient. In addition, contraction of rescuer muscles groups will cause movement and add to the force applied. A rescuer has inherent physical attributes that could be limited or rendered ineffective due to poor rescuer posture.

To conduct research into this field a group of trained BLS providers are required. An appropriate manikin is required to present similar chest characteristics of an adult patient. Motion analysis equipment is required to measure rescuer posture at different platform heights. A force plate is necessary to aid the origins of rescuer forces and the effects of platform height on those forces.

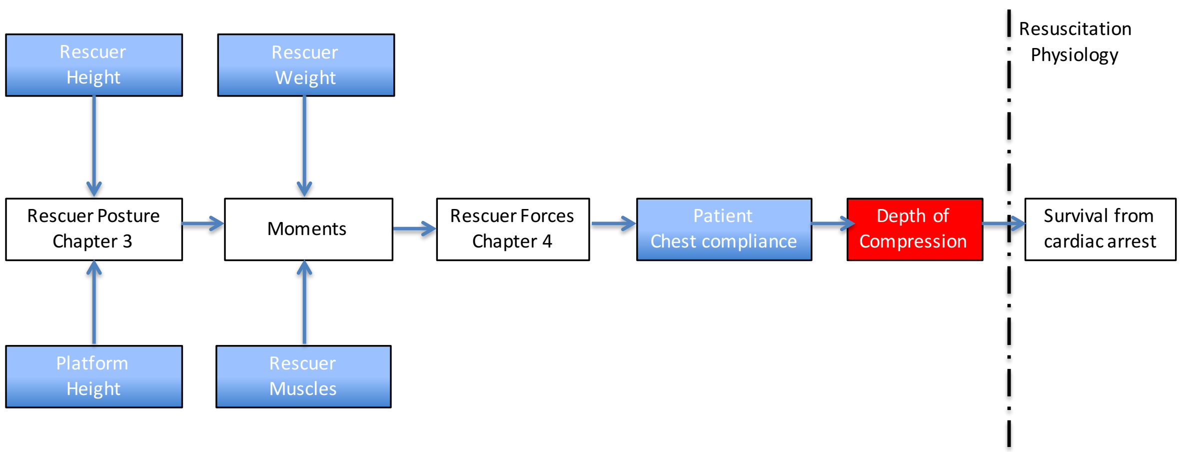


Figure 1-8 A schematic outline of the programme of work.

Therefore it is proposed platform height effects the quality of chest compressions (Figure 1-8). Furthermore, platform and rescuer height will determine rescuer posture, during an in-hospital cardiac arrest. Rescuer posture could have a direct impact on the rescuer attributes i.e. mass, muscles and movement used to create and deliver rescuer forces. The magnitude of rescuer forces will manifest as depth of chest compressions. Ultimately, the depth of compression achieved during BLS will determine the resuscitation physiology and influence patient survival.

The aim of the thesis is to determine if platform and rescuer height affects the depth of compression achieved during a simulated in-hospital cardiac arrest. To measure rescuer posture across a range of clinically relevant platform heights. To determine the origins of rescuer forces and evaluate the impact of rescuer posture on those forces

2 Materials and Methodology

The research described in this thesis is to determine the impact of platform height on the depth of compression during a simulated in-hospital cardiac arrest. The theory proposes a geometrical model based on platform and rescuer height to predict rescuer posture; the effect of rescuer posture on the ability of the rescuer to generate force from upper body moments onto an instrumented manikin that determines the depth of compression (figure 2-1).

This chapter presents the methods and materials used to measure rescuer posture (**chapter 3)** and rescuer forces (**chapter 4**) in a group of trained rescuers performing BLS on an instrumented manikin, during a simulated in-hospital cardiac arrest (figure 2.1). The methodology draws upon the analytical review of existing studies (chapter 1) and resuscitation guidelines to provide clarity and develop novel concepts. Finally, to maximise the opportunity for translation into clinical practice, the methodology will incorporate criteria and elements from key simulation literature[120].

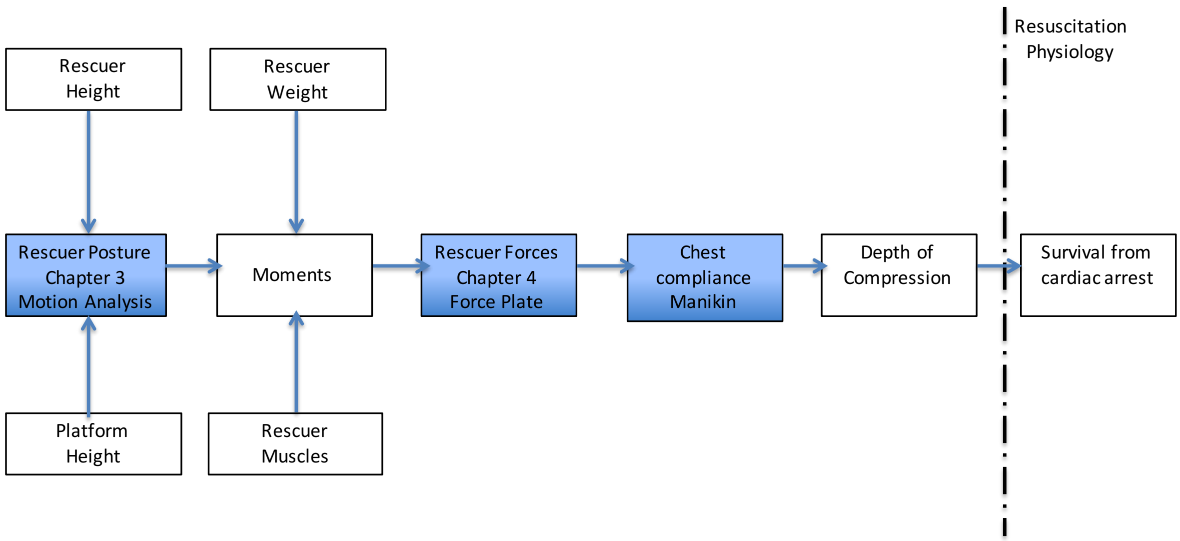


Figure 2-1 Overview of thesis identifying the required methods and modalities (shaded blue).

The simulated cardiac arrest scenario is based upon the clinical environment and considers the range of heights a medical platform could be positioned during an in-hospital cardiac arrest. A review and audit of medical platforms is required (section 2.1.3).

Depth of compression will be measured from an instrumented manikin. To translate findings to clinical practice, the resuscitation manikin requires chest compliance similar to an adult human chest. A review and evaluation of resuscitation manikins is necessary (section 2.2.2).

A motion detection system is required to determine the posture of rescuers in relation to the resuscitation manikin during BLS. The motion detection system is required to record anatomical rescuer landmarks during the delivery of compressions to determine rescuer posture (section 2.3.2).

To identify forces and the transfer of forces, a ground reaction force plate is necessary to determine forces generated by the rescuer and delivered to the resuscitation manikin. These measurement systems will permit accurate positional and performance data to be recorded during simulated cardiac arrests (section 2.3.4).

2.1 Medical Platform

2.1.1 Requirements

In order to replicate the resuscitation scenario, the platform used for the studies was chosen to accurately replicate the clinical situation for key attributes whilst minimising the effect of confounding variables. Consideration was therefore given to: the range of platform heights encountered, surface compliance, distance between rescuer and patient, and surface friction.

Platform Heights

As was described in chapter 1, the range of platform heights used clinically is defined by British Standards as 400 mm to 800 mm. However, this does not include the mattress upon which the patient rests. Mattresses are typically 150 mm in depth bringing the height of the surface upon which patients are placed to between 400 mm + 150 mm = 550 mm and 800 mm + 150 mm = 950 mm. For the studies described in this thesis it was necessary therefore to identify a platform that can be adjusted between 550 mm and 950 mm.

Surface Compliance

The effect of mattress compliance has been studied elsewhere[81,121,122] and is not the focus of this thesis. To rule out compliance as a potential confounding variable a non-compliant surface is required for these investigations.

Platform Width

Patients may be resting at any point across the width of the bed when they go into cardiac arrest. This introduces a positional uncertainty into measurements and hence it was decided to standardise by ensuring that during the study the victim would be adjacent to the rescuer. This requires a platform width similar to the width of the patient.

Surface Friction

Finally, it is necessary to control the friction of the surface as a failure to ensure adequate friction between surface and patient would potentially result in the patient moving horizontally in an atypical manner during chest compressions.

2.1.2 Platform Solution

An examination couch was considered a suitable solution and was sourced.

A Physio-Med™ Model (PP125) (fig 2-2) has a non-compliant surface that can be adjust to a height between 480mm and 980 mm. This range marginally exceeds the range of surface heights encountered in a clinical environment. It has a width of 620 mm which accommodates the width of the resuscitation manikin. Figure 2-2 illustrates how the platform height may be adjusted using the foot pedal and the height measured using a ruler.

Figure 2-2 A Physio-Med platform illustrating the foot pedal for height adjustment and a measure.

2.1.3 Distribution of Medical Platforms - Audit

Despite identifying a range of platform heights (Table 2), it is unclear as to the national distribution of medical platforms within the NHS. Communication (e-mail NHS supplies 2013) between the author and NHS supplies failed to identify the distribution of makes and models of medical platforms in current use, despite a centralised purchasing system. Therefore, the author undertook an audit of the distribution of medical platforms. Direct communication between the author and three acute trusts in the South of England revealed the following distribution for their main manufacturer (Table 4)[123].

Table 4 Distribution of Medical Platforms across three NHS trusts

Manufacturer	Location	Model	Number of beds
Arjohuntleigh	UHS	480/460	249
Arjohuntleigh	UHS	560/880	882
Arjohuntleigh	PHT	560	1200
Arjohuntleigh	HFFT	8000	460

Therefore, the platform required for this study must operate across a range of 50 cm and be capable of being positioned at any height between 480 – 980 mm. To limit confounding variables, the platform must be non-complaint and be able to accommodate an adult manikin.

2.2 Patient

The studies described in this thesis require measurements of depth of compression to be performed over a variety of platform heights some of which may well be ineffective. Investigations based upon patients in cardiac arrest over such a wide range of bed heights would be neither ethical nor practical. Similarly, measurements on a volunteer in sinus rhythm also present health risks and is therefore not ethically justified. For these reasons, the studies were constrained to simulating a patient in key aspects. However, manikins have been used for training purposes for many years and offer a potential solution.

2.2.1 Requirements

Previously, it was revealed that human chest characteristics are curvilinear (Figure 1-7) and resuscitation manikins are typically fitted with a compression spring to mimic chest characteristics[77,79]. A device and system to accurately measure the depth of compression from the manikin was required. Further considerations include the size and weight of the manikin to replicate an adult patient with limbs, positioned on the platform[120]. A robust manikin to withstand repeated BLS activity.

2.2.2 Solution

A review of instrumented manikins is required to achieve an appropriate chest compliance[77-79,124] for experiments in chapters 3 and 4.

Aim

Establish an instrumented resuscitation manikin that simulates the force-depth relationship of the adult human chest[77,125]. Instrumentation must accurately measure and record depth of compression, decompression and the interval between compressions to permit detailed analysis of a resuscitation episode, including the rate of compressions.

A Review of Commercial Resuscitation Manikins Chest Characteristics

Instrumented resuscitation manikins typically employ a compression spring as a resistive force for the rescuer to push against[124]. Compression springs demonstrate a linear response ($F=-Kx$) (F = force (N), K = spring constant (N/m) and x = displacement (m) to the force applied. Two studies have reviewed the characteristics of commercial instrumented manikins[78,124]. A study by Baubin[124] investigated 8 resuscitation manikins using a mechanical thumper, an automated device to compress the chest, that demonstrated 8 different chest compliances. Baubin et al[124] revealed a range of forces (274 – 529 N) was required to compress a chest 40 mm[19] for the range of manikins.

To maximise clinical application, a review of existing training manikins was required. A review of four commercially available manikins; within an acute NHS trust was performed by the author. The manikins' chest compliance were tested using calibrated 50 N weights and a digital micrometre (+/-0.02 mm) (RS Components). Each resuscitation manikin was tested 5 times with the incremental application and removal of the calibrated weights, up to 600 N.

Table 5 A summary of the chest compliance characteristics of four commercially available manikins within an acute NHS trust.

Manikin	**1**	**2**	**3**	**4**
Compliance N/mm	9.1	8.8	9.2	12.7

The results obtained demonstrated all four manikin's chest compliances were inconsistent with adult human chest parameters[77,79]. Therefore, existing commercial manikins within the NHS trust were less compliant i.e. more resistive, than an adult human chest and therefore not considered appropriate for this study. A new resuscitation manikin with appropriate adult chest compliance was required.

Development of an Instrumented Manikin

A decommissioned resuscitation manikin was sourced by the author and commenced the removal of existing spring and circuitry. The new experimental manikin was created and fitted with a compression spring (spring constant 9.15 N/mm, Lee Springs (UK) between the anterior and posterior chest wall of the manikin (fig 2.3). The spring was housed in a polycarbonate tube that permitted anterior posterior movement when the chest was compressed. The superior aspect of the spring was attached to a mechanical arm that was connected to a rotary voltage potentiometer. The movement of the mechanical arm during compression was detected by the voltage potentiometer powered by 2 x 9 Volt batteries. The output of the voltage potentiometer was sampled and digitised by bespoke software.

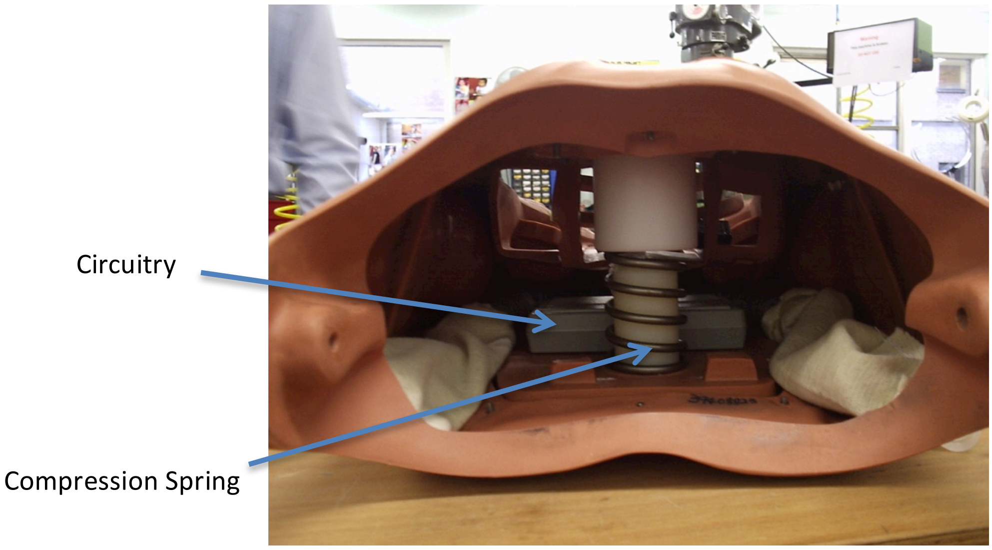


Figure 2-3 The internal view of an instrumented manikin demonstrating the compression spring and circuitry compartment.

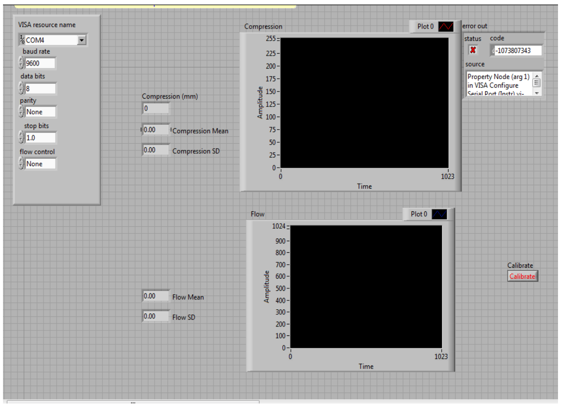
Mancal and Analysis VI

To permit the digital measurement of the chest compression. Software was written using Labview 8.6 Virtual Instrument for the manikin calibration process and the measurement of chest compressions for the experiments. The bespoke software was written by the medical Physics team, University Hospital Southampton. A screen shot of the calibration programme is presented in figure 2.4 b.

Manikin Calibration

To ensure accuracy of the resuscitation manikin and human chest characteristics, a series of calibration studies were performed in the Medical Physics laboratory, University Hospital Southampton. Using a test jig, the instrumented spring loaded manikin was subjected to incremental calibrated 50 N weights in ascending and descending order up to a maximum of 600 N whilst connected to the recording software programme (Figure 2-4).

a) Calibrated weights being applied to manikin's chest



b) bespoke software screenshot

Figure 2-4 a) Calibration of the manikin using calibrated 50 N weights and b) calibration software.

The instrumented manikin was connected to a Labview 8.6 Virtual Instrument (VI) (Texas Instruments, 2008) software programme via a USB to serial port cable. The Manikin calibration programme was written by Medical Physics, University Hospital Southampton, sampled the voltage output from the voltage potentiometer and converted the analogue voltage output into a digital value. Sampling was performed for 10 secs for each calibrated 50 N weight, either added or subtracted.

On completion of the sampling period a mean digital value and standard deviation was calculated by the software programme. Simultaneously the depth of compression was recorded using a digital micrometre (+/-0.02 mm) (RS Components).

The calibration process, ascending and descending up to 600 N, was repeated on three separate occasions within the Medical Physics Laboratory. The digital values were plotted against the measured depths of compression and a regression formula derived using Excel (Microsoft 2007) (Figure 2-5).

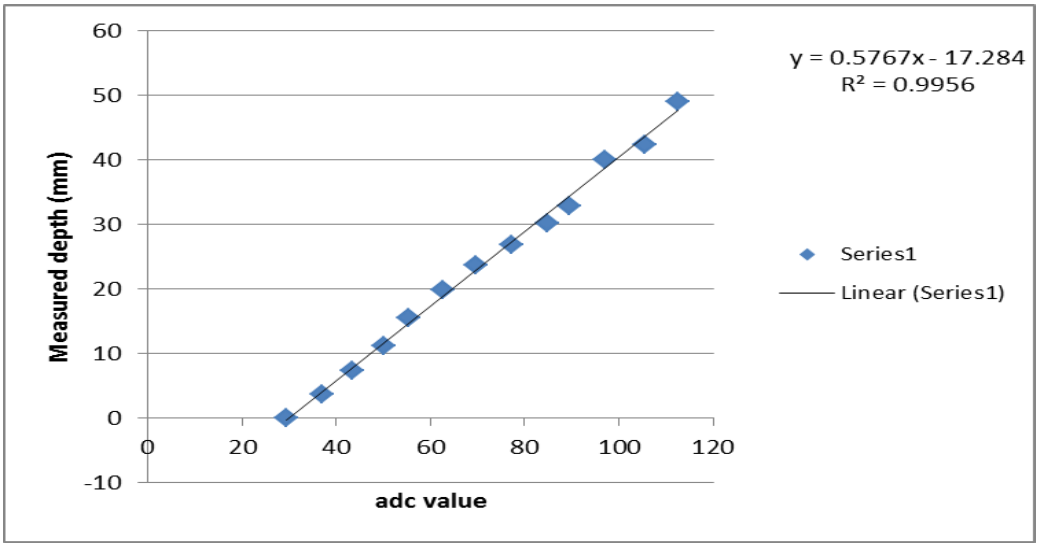


Figure 2-5 The line graph presents the correlation between adc (digital) values and measured depth of compression for each 50 N weight. The regression formula was calculated from the data using Excel.

Manikin Validation

Validation of the calibration dataset employed the Excel (2007) derived regression formula (y = 0.5767x - 17.284) that was programmed into the Mancal VI. This formula was used to assess the accuracy and reproducibility of the instrumented manikin for depth of compression data. The manikin's chest was subjected to a 500 N weights, intended to cause a deflection of 40mm. The depth of compression was recorded using a digital micrometre (+/-0.02 mm); in addition, the Mancal VI also recorded a computed depth of compression by utilising the digital value and applying the regression formula to produce a computed depth of compression. The application and removal of the 500 N weight was performed 10 times and the mean of the 10 samples derived.

Manikin Calibration

The differences between the measured depth of compression and the computed values were compared for accuracy using a Bland-Altman plot. Data obtained for the incremental addition and subtraction of 50 N weights, demonstrated a linear response with a small degree of hysteresis. The plotted data presented a R^2 of 0.9956 and a regression equation (Figure 2-6). This is evidence that all data points lay very close to the line of best fit.

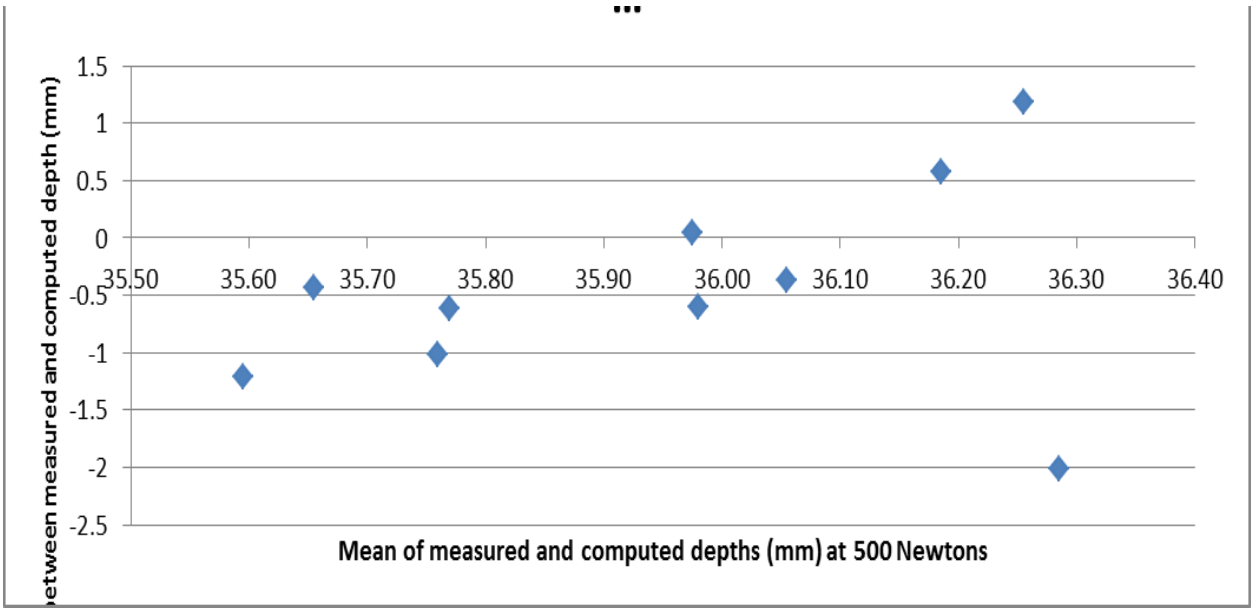


Figure 2-6 Bland-Altman plot of the mean differences between computed and measured depths of compression at 500 N, using 50 N increments.

Manikin Validation

The mean of the ten computed depths, with the application of 500 N, was 36.2 mm (SD 0.44) the mean of the measured depth (electronic callipers) was 35.7 mm (SD 0.58). The mean of the differences between the ten computed depths and measured depths was 0.45 mm (SD 0.91). Comparison between the ten measured depths and computed depths reveal a difference of 1.0%.

The removal, decompression, of the calibrated weights and restoration of the chest's resting position demonstrated a computed mean of 0.74 mm (SD 0.23) and a measured mean of 0.28 mm (SD 0.43). The mean of the differences was 0.41 mm (SD 0.30).

The minor difference between the computed depths and measured depths are due to a combination of random and systematic errors. The random errors would suggest the mechanical properties of the manikin's chest, including hysteresis. The systematic errors would suggest the electronic circuits/software.

Manikin Laboratory Pre - Experiment

Prior to the laboratory experiments (chapters 3 and 4), the resuscitation manikin was fitted with limbs to simulate an adult human patient. The lower limbs were attached to the base of the upper body (Figure 2-7). The manikin was re-calibrated with limbs attached to ensure chest compliance was similar to a human chest.

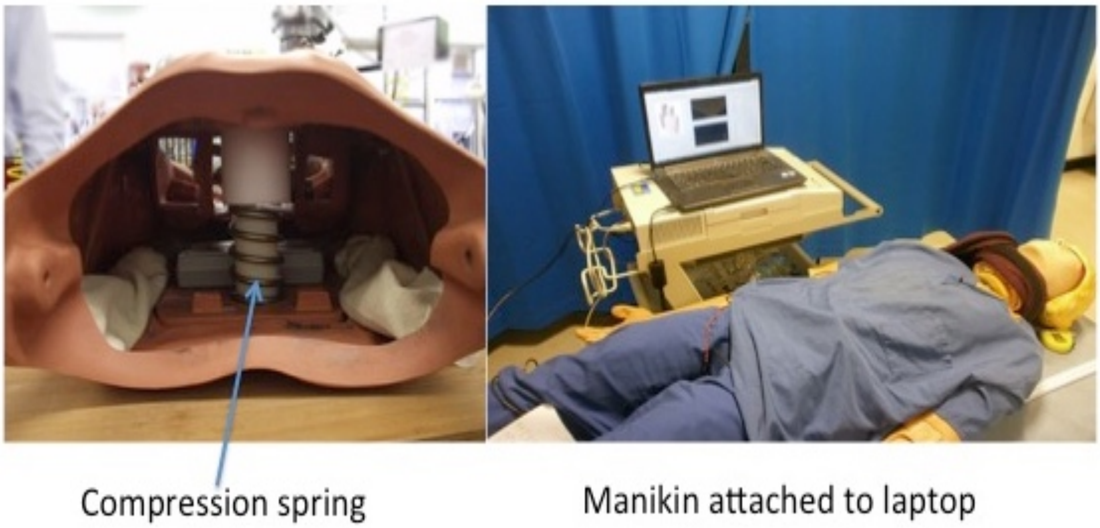


Figure 2-7 Manikin upper body demonstrating connection for lower limbs

To verify the system was suitable for use, qualified BLS members of staff conducted three laboratory-based pilot tests. These members of staff were excluded from the subsequent experiments. The Analysis (VI) correctly identified each peak from which digital values could be read. Depth of compression data was calculated by deducting peak depth of compression from residual depth of compression (figure 2.8).

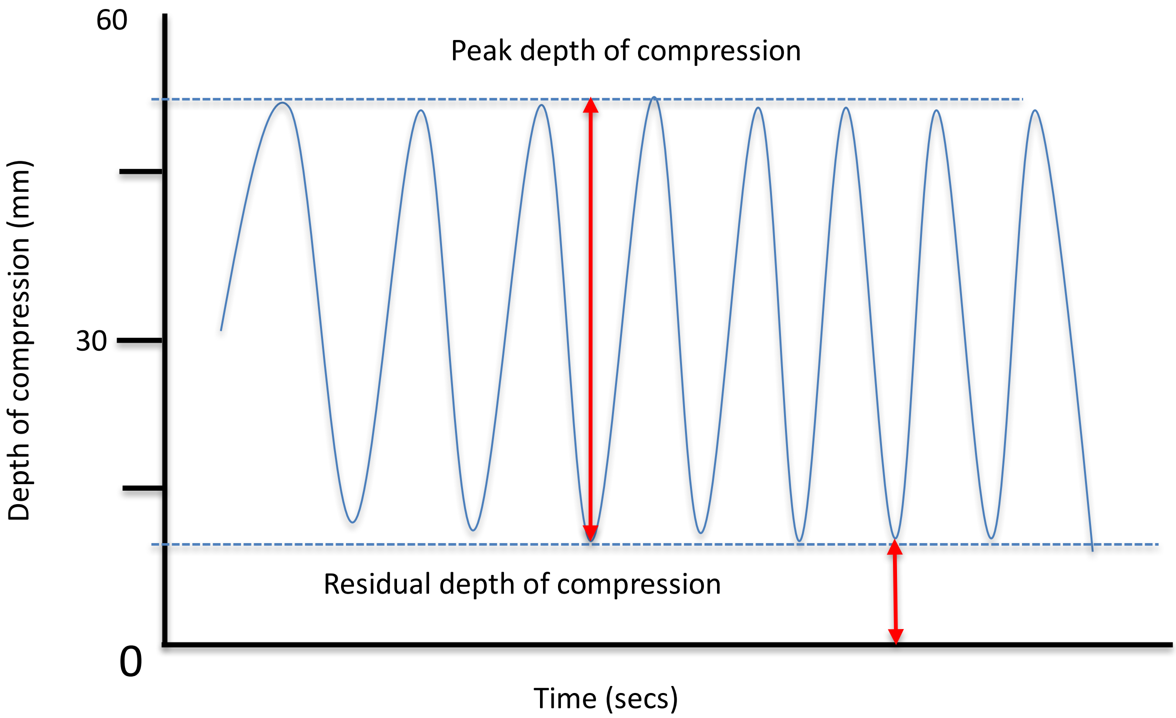


Figure 2-8 A graph demonstrating peak and residual depth of compression.

Post Experiments

On completion of the experiments for this thesis the manikin was recalibrated to check for accuracy. Five readings with calibrated 50 N weights, up to 500 N were recorded. The differences between the depths of compressions were analysed. The instrumented resuscitation manikin was re-calibrated prior to and post experimental phase of the research. 50 N weights were placed incrementally onto the manikin's chest and depths of compression and decompression were measured using electronic callipers. A chest compliance of 7.5 N/mm was recorded. The chest compliance characteristic was and is within the range of an adult human chest.

2.2.3 Conclusion – Resuscitation Manikin

Existing commercially available manikins did not replicate the compliance of an adult human chest. Therefore, a new experimental manikin was required. The experimental manikin was correctly instrumented and calibrated for the impending experiments. The manikin chest characteristics were in the range of an adult human chest and had demonstrated an acceptable level of accuracy and repeatability. Finally, the manikin reflected a human adult patient on a medical platform and was robust to endure repeated chest compressions.

2.3 Rescuer

It is proposed rescuer posture affects the quality of chest compressions during a simulated cardiac arrest. Therefore, an anatomical motion analysis system was required to detect and record rescuer posture and movement during BLS for chapters 3 and 4. Measurement and quantification of rescuer posture and motion will permit analysis of the effects of platform height with respect to the quality of chest compressions.

2.3.1 Rescuer Posture Measurement - Technical Requirements

The motion analysis system must be capable of recording the static and dynamic movement of rescuers performing chest compressions across a range of clinically relevant platform heights. The rate of chest compressions was 120 bpm therefore a sampling frequency of greater than 20 Hz would exceed the Nyquist limit and avoid aliasing. However, a much higher sampling frequency would improve resolution.

The motion system was required to record for a range of human movement in 3 axes. Movement of the rescuer trunk through a range of 90° to account for the flexion and extension of the rescuer's back, and the movement of the rescuer arms through a range of 180° was required.

Furthermore, the motion analysis system was required to produce a 2D animation of the rescuer at each platform height to analyse rescuer movement during the delivery of BLS. The author approached the Experimental Officers in the Faculty of Health Science, University of Southampton to investigate potential motion analysis equipment. The CODAmotion system was available for these experiments provided it was capable of accurately recording rescuer posture and movement during the delivery of BLS.

The CODA (Cartesian Optoelectronic Dynamic Anthropometer) system has been used in a range of clinical studies and undergone a review with similar systems[126]. Richards et al[126] had commented on the accuracy as being with 0.1 mm and 0.3°. CODAmotion was capable of generating an animated 3D image of a rescuer using strategically placed sensors.

2.3.2 Rescuer Posture Measurement - Solution (CODA System)

The CODA[127,128] system was identified to record participants in 3 dimensions (X, Y and Z coordinates). The system is comprised of two mpx30 sensors. The sensors accommodate three optical scanners on a frame sampling at 50 Hz (Figure 2.9). Sensors detect infra-red CX markers (fig 2.10) placed on anatomical rescuer landmarks. Each CX marker indicated the position of specific anatomical landmarks of the rescuer by emitting a 50 µs infra-red flash. Angular resolution was 0.002°, lateral resolution 0.05 mm and distance resolution 0.3 mm[129] for the normal working range. These operational specifications determined the CODA system as appropriate for these investigations.

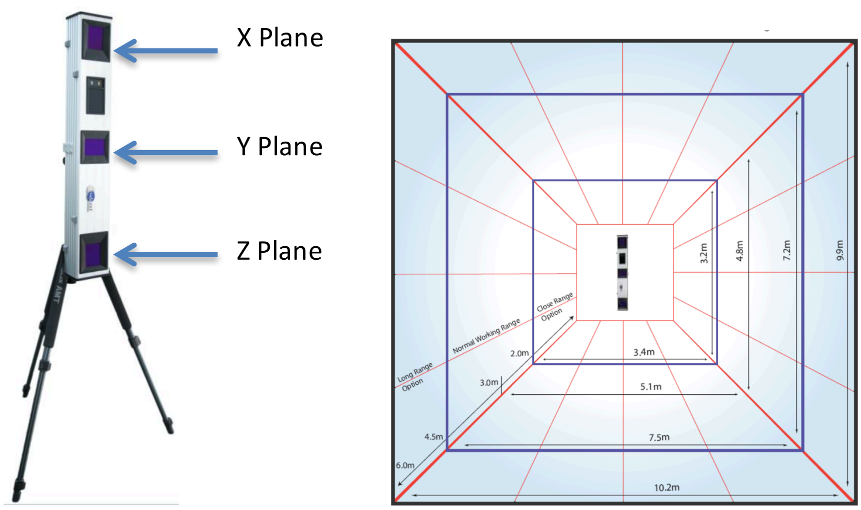


Figure 2-9 mpx30 3D Sensor (left) and the normal working range (right) (CODAmotion Charnwood Dynamics)[127]. Images reproduced with permission, CODAmotion.

Methodology

The geometrical relationship between the rescuer and the instrumented manikin was recorded using the 3D motion analysis and was performed with the CODA mpx30 masked linear arrays (MLAs) (version 5.46) system. Eight active CX markers (infra-red Light Emitting Diode) (fig 2.10) with drive boxes were positioned on the rescuer's body. The angles of the rescuer's shoulders (RAA) and back (RAB) were measured and recorded during the delivery of chest compressions at each platform height.

Figure 2-10 A CODA CX marker(CODAmotion Charnwood Dynamics). Imaged reproduced with permission, CODAmotion.

Additional markers were used to produce a 3D linear image of the rescuer.   The angle between the vertical plane and the shoulder determined RAA. The angle between the rescuer hip and top of the spine determines the RAB (figure 2.11).

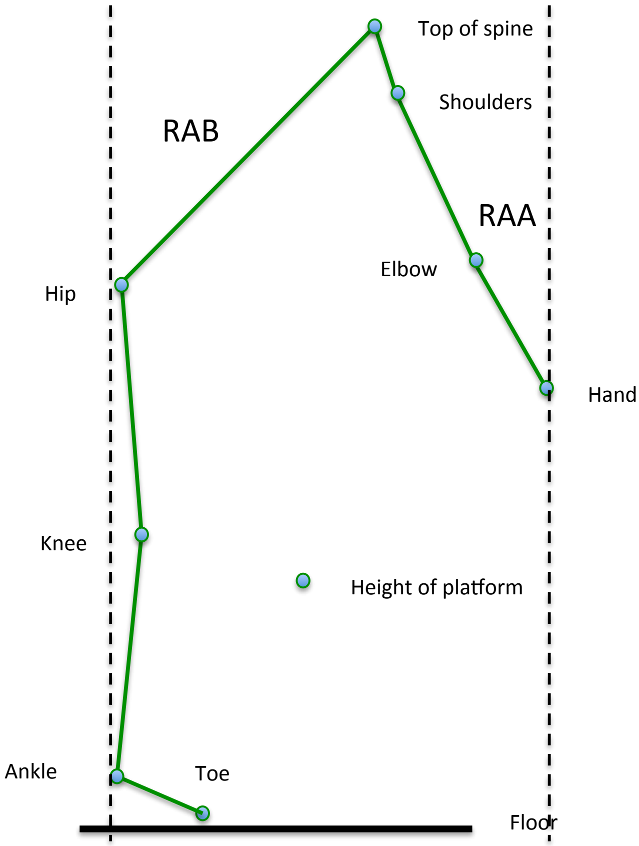


Figure 2-11 A CODA image of rescuer posture derived from sensor markers demonstrating RAB and RAA.

CODA data collection

All recorded CODA data was processed within the CODAmotion™ software and exported into Excel (2007). Within Excel RAB and RAA were calculated for each rescuer at each platform height.

2.3.3 Rescuer Forces - Requirements

A forces system is required to measure the proportion of force transferred from the rescuer to the resuscitation manikin (chapter 4). To investigate the origin of forces and the transfer of forces from the rescuer to the manikin, a ground force plate was required to measure forces during prescribed resuscitation procedures.

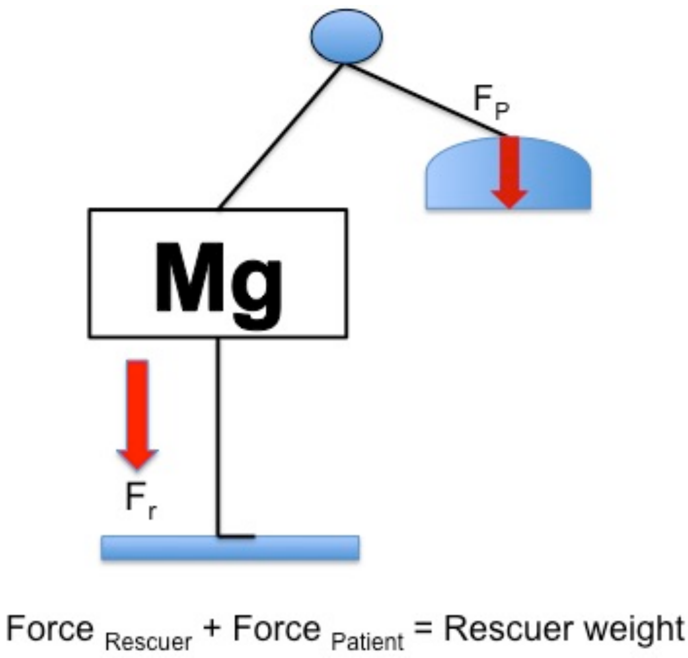


Figure 2-12 Schematic demonstrating rescuer forces for leaning and pushing.

A rescuer has inherent upper body attributes i.e. mass and muscles, which are used to compress the manikin's chest. Therefore, a rescuer standing on a force plate presents, assisted by gravity, their total body weight (Mg) to the plate. As the rescuer performs specific functions, leaning and pushing, the force is transferred from the rescuer to the manikin. The force plate will present a lower force as the prescribed functions are performed.

The forces generated and transferred by the rescuer population to the manikin require a ground force plate to operate over a range of 0 – 1500 N. The range has to encompass the weight range of the qualified BLS rescuers and the forces they can generate during the delivery of chest compressions. The force plate system has to be responsive to changes during chest compressions delivered at 120 bpm and measure forces in the vertical (Z) plane. The force plate must be responsive to changes in force and sample data at a rate greater than 20 Hz. A higher sampling frequency will improve the resolution of forces.

2.3.4 Rescuer Force – Solution (Kistler Force Plate)

The Biomechanical Laboratory, University of Southampton accommodates the Kistler 9281B force plate with the amplifier 9865D[130]. This system (figure 2.13) permitted the measurement of forces in 3D and sampled at 1000 Hz per second with an operating range of -10 kN to +20 kN (accuracy +/- 0.5% across the range). The frequency response of the Kistler 9281B system was 600Hz. The force plate will permit the measurement of forces derived from the rescuer and those transferred from the rescuer to manikin to be recorded. The functionality and operating characteristics of the force plate address the requirements of the experiments for chapter 4).

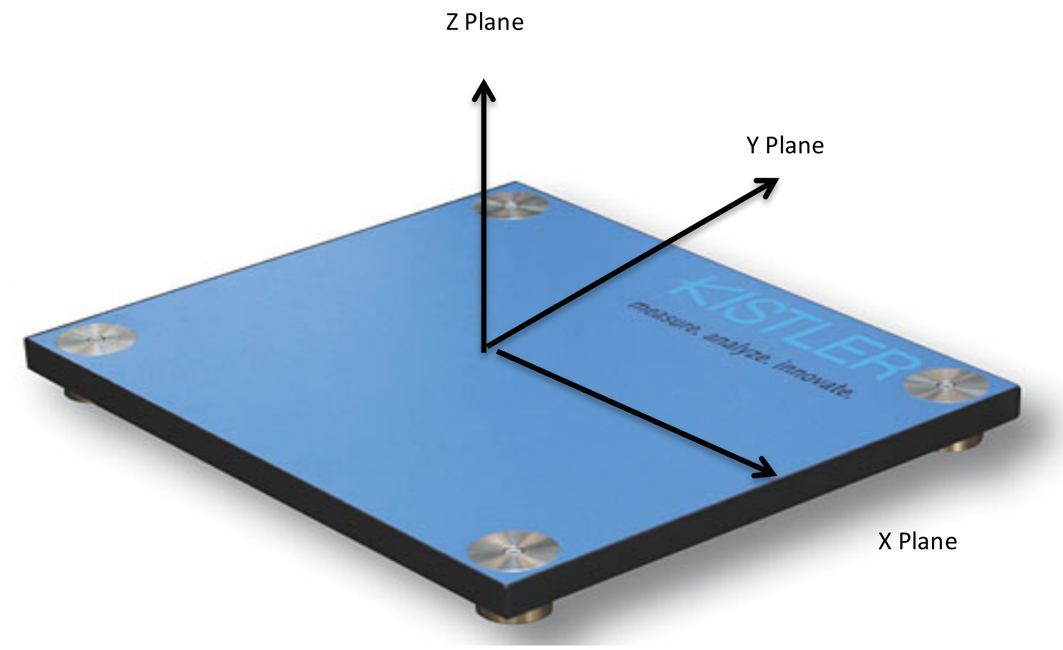


Figure 2-13 Kistler Force Plate model 9821B[130] demonstrating three (x, y & z) planes modified by the author. Image reproduced with permission, Kistler.

Conclusion

The materials and methods described permitted accurate collection of postural and performance data. A review of medical platforms ensure the results of the thesis could be applied to the clinical environment. The instrumented manikin was designed and constructed to simulate the adult human chest characteristics and to provide accurate depth of compression information. CODA measurement allowed the posture of the rescuer in relation to the manikin to be recorded for each randomised platform height and permitted evaluation of the geometrical model (chapter 3). Force data was produced by the force plate system identifying the origins of force, the transfer of forces from the rescuer to the manikin. It will also provide data to evaluate the forces concept (chapter 4).

Summary of Chapter 2

To optimise the quality, accuracy and translation of data, the resuscitation environment has been explored and appropriate equipment has been identified. Previous studies have been evaluated and identified potential failings, thereby ensuring the cardiac arrest environment for these experiments are physically matched with an in-hospital cardiac arrest. In addition, data measurement systems have been identified to accurately record kinematic, kinetic and depth of compression data.

3 An investigation of the relationship between platform height, rescuer posture and depth of compression

It was hypothesised in chapter 1; during an in-hospital cardiac arrest, the height of the medical platform and rescuer determines rescuer posture in relation to the patient. Moreover, rescuer posture is associated with the efficacy of chest compressions (Figure 3-1). This chapter investigates the mechanisms of performing BLS during a simulated in hospital cardiac arrest. It proposes a novel geometrical model for predicting rescuer posture during simulated in-hospital cardiac arrest and investigates the relationship between platform height and the quality of resuscitation.

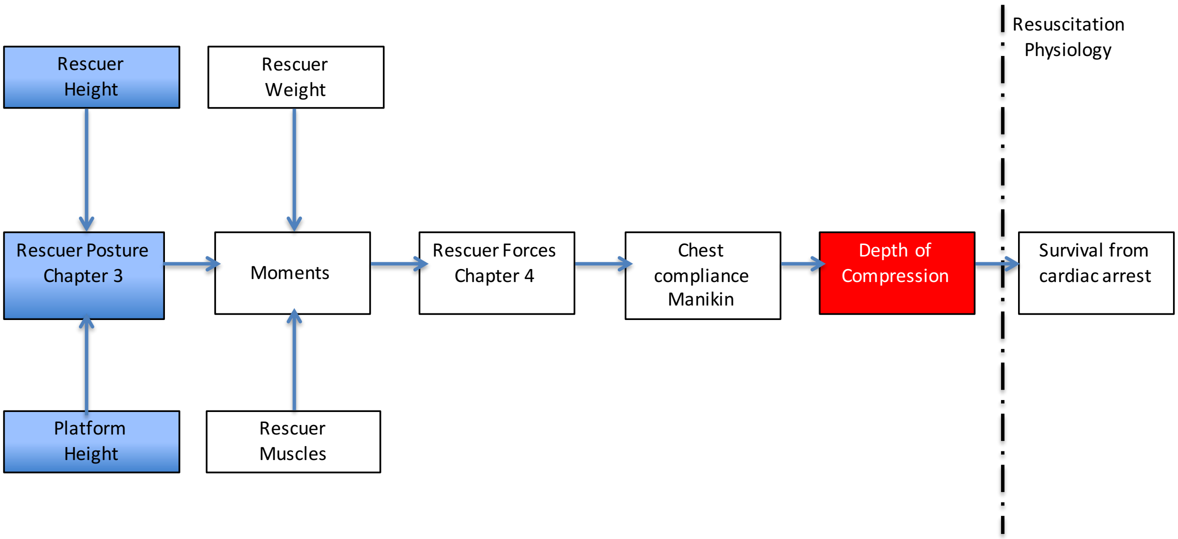


Figure 3-1 Overview of thesis and indication of geometrical aspect of chapter 3

The novel geometrical model, using mathematical concepts and anthropometric data, predicts rescuer posture in relation to a victim in a simulated in-hospital cardiac arrest. The model could identify those rescuers at risk of sub-optimal posture and potentially an association between platform height and poor quality BLS. Analysis of current literature identified previous work and explored opportunities to maximise clinical relevance.

3.1 Aims of Chapter 3

Previous studies into the effects of platform height on resuscitation provided contrasting observational data[81,83,84,88,89,91] and not a model based upon the rescuer and platform height. Existing studies failed to examine a range of heights at which a medical platform could be positioned during an in-hospital cardiac arrest. Using a range of clinically relevant platform heights, this work using a geometrical model will confirm the mechanisms affecting rescuer posture during a simulated cardiac arrest. It will analyse the effects of platform and rescuer height on rescuer posture and the quality of chest compressions delivered during a cardiac arrest.

Aim 1: To determine the impact of platform height on the quality of chest compressions, for a range of clinically relevant platform heights, during a simulated cardiac arrest.

Aim 2: To determine the impact of rescuer height on the quality of chest compressions, for a range of clinically relevant platform heights, during a simulated cardiac arrest.

Aim 3: To develop and evaluate the efficacy of a geometrical model to predict the posture of a rescuer, for a range of clinically relevant platform heights, during a simulated cardiac arrest.

3.2 Theoretical Analysis of Factors affecting Posture

Based upon the photographic evidence presented in chapter 1, a simple geometrical model is proposed and the following nomenclature are adopted. The angle between the rescuer shoulders and the centre of the patient's chest in the vertical axis is identified as Rescuer Angle Arms (RAA) (Figure 3-2). The angle of the rescuer back in relation the vertical axis is termed Rescuer Angle Back (RAB)(Figure 3-2). RAA is considered to be at 0° when the rescuer shoulders are positioned vertically over the centre of the manikin's chest, as recommended by resuscitation guidelines[18,36,55,58]. RAB is considered to be at 0° when the rescuer's back is vertical.

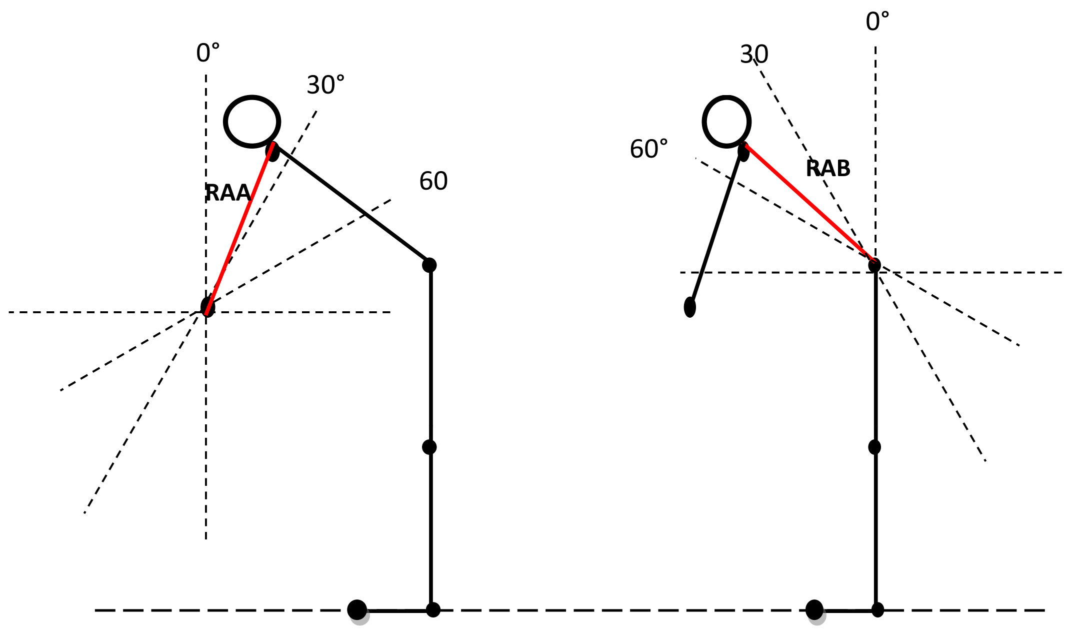


Figure 3-2 Schematic demonstrating rescuer angles, RAA and RAB (lateral view).

The model is required to predict RAA and RAB for a range of clinically relevant platform (chapter 2) heights and rescuer heights. The geometrical model is based upon trigonometry, anthropometric data[104] and the following assumptions:

- The horizontal distance between the rescuer and the patient is constant
- Rescuer spine and arms are straight
- Rescuer upper body pivots at the hips
- Rescuer hands are positioned on the centre of the patient's chest
- Rescuer legs are straight and vertical
- Rescuer feet are flat on the floor
- The platform is non-compliant
- Patient chest depth is 25 cm

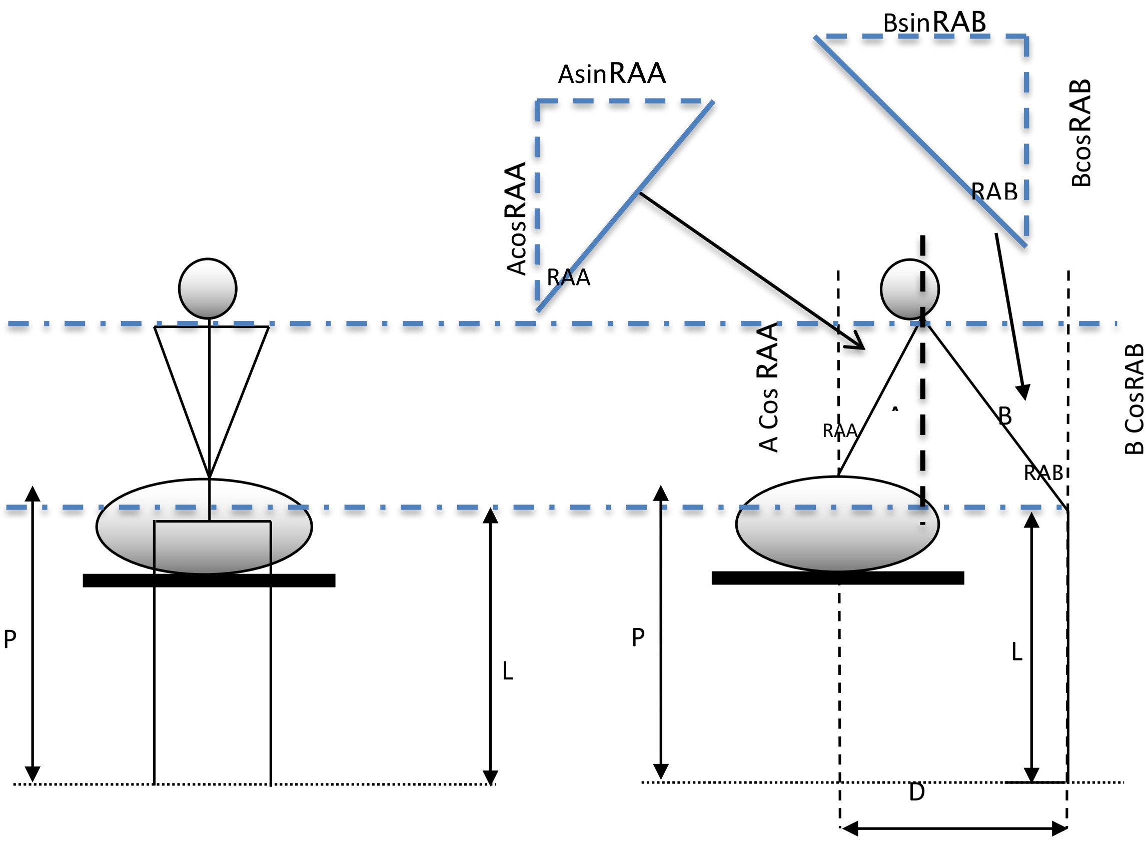


Figure 3-3. A Schematic of geometrical model (frontal and lateral views).

A – Length of Rescuer Arm (shoulder to wrist) B - Length of Rescuer Back (hip to C5) P - Height of patient's Chest L - Height of Rescuer Hip (floor to hip)	D - Chest centre to Hip distance RAA– Angle of Rescuer shoulder to vertical RAB- Angle of Rescuer back to vertical

3.2.1 Mathematical Model for Rescuer Geometry

As the arms meet the trunk at the shoulders, the height of the rescuer hips (L) and the vertical height of the rescuers back (B) must be equal to the height of the victim's chest (P) and the vertical height of the rescuer arms (A) (Figure 3-3). Equation 1 and 2 equate the vertical and horizontal components of the geometrical model, respectively. Both equations must conform to trigonometric identity (equation 5) and are rearranged to equate RAA (equation 8) and RAB (equation 12) for a range of, relevant, platform and rescuer heights.

Vertical component

$$L + bcos\mathrm{RAB} = P + acosRAA \qquad \text{Equation 1}$$

Horizontal component

$$d = bsin\mathrm{RAB} + asinRAA \qquad \text{Equation 2}$$

Rearranging equation 1:

$$cos\mathrm{RAB} = \frac{P - L + acosRAA}{b} \qquad \text{Equation 3}$$

Rearranging equation 2

$$sin\mathrm{RAB} = \frac{d - asinRAA}{b} \qquad \text{Equation 4}$$

Using trigometric identity

$$cos^2\text{RAB} + sin^2\text{RAB} = 1$$ Equation 5

Using equation 3 and 4 and inserting into equation 5:

$$\left(\frac{P-L+acosRAA}{b}\right)^2 + \left(\frac{d-asinRAA}{b}\right)^2 = 1$$ Equation 6

$$(P - L + \text{a}\cos RAA)^2 + (d - asinRAA)^2 = b^2$$ Equation 7

$$(P - L + acosRAA)^2 + (d - asinRAA)^2 - b^2 = 0$$ Equation 8

Solving for RAB

Rearranging equation 1 and 2;

$$cosRAS = \left(\frac{L - P + bcos\text{RAB}}{a}\right)$$ Equation 9

$$sinRAS = \left(\frac{d - bsin\text{RAB}}{a}\right)$$ Equation 10

However

$$cos^2RAA + sin^2\text{RAA} = 1$$ Equation 11

Therefore

$$\left(\frac{L-P+bcos\text{RAB}}{a}\right)^2+\left(\frac{d-bsin\text{RAB}}{a}\right)^2=1$$ Equation 12

$$(L-P+bcos\text{RAB})^2+(d-bsin\text{RAB})^2=a^2$$ Equation 13

$$(L-P+bcos\text{RAB})^2+(d-bsin\text{RAB})^2-a^2=0$$ Equation 14

3.2.2 Predicted Rescuer Geometry

For a given platform and rescuer height, the only unknown in equation 8 is RAA and equation 12 is RAB. In order to identify the values of RAA and RAB to the nearest 0.1°, different values were calculated using Excel (Microsoft 2007). The range of platform heights were based upon the range of heights a medical platform could be positioned clinically (48 to 98 cm)[92-94] (chapter 2). A range of rescuer heights (1.5, 1.76 and 2.0 m) was used to predict the relationship between platform height and rescuer angles (RAA & RAB) (Figure 3-4). For the experiment, measured rescuer height was used in the model to predict rescuer posture.

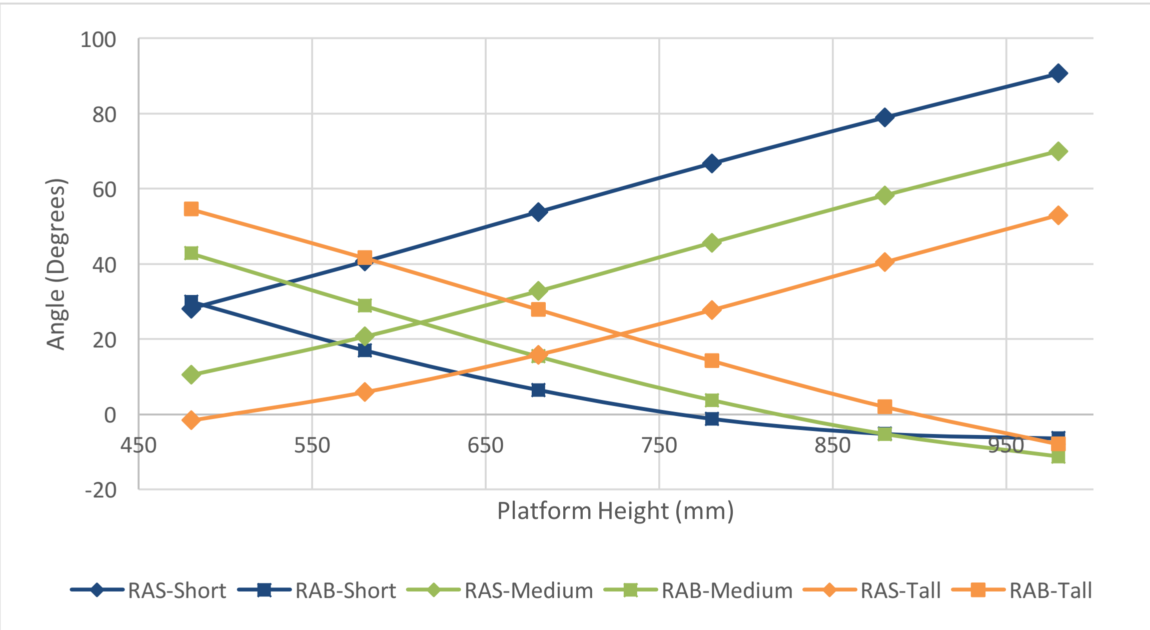


Figure 3-4 A line graph demonstrating predicted RAB and RAA for a range of rescuer heights (1.5 (short), 1.76 (medium) & 2.0 m (tall)) across a range of platform heights.

Predicted RAA

The geometrical model predicted; as platform increased, RAA increased, for a short (1.5 m), medium (1.76 m) and tall rescuer (2.0 m). These predictions would suggest rescuer height is also a contributing factor towards rescuer posture. The graph demonstrates an almost linear relationship for RAA for the three individual rescuers, with the lowest RAA for the tallest rescuer. Interestingly, for the tall rescuer (2.0 m), the model predicted a negative RAA at platform height 48 cm. This prediction would suggest the rescuer is in a hyper-flexed posture and move the centre of rescuer mass outside the base of the rescuers feet. This would potentially destabilise the rescuer during chest compressions.

Furthermore, the model predicted the short and medium height rescuer would be unable to adopt resuscitation guideline posture at the lowest platform height (48 cm), (RAA 28.0° and 10.4° respectively). Data from the graph (Figure 3-4) has been translated into scaled linear diagrams (

Figure 3-5) and present predicted rescuer posture for the short (1.5 m), medium (1.75 m) and tall (2.0 m) rescuer at the lowest platform height (48 cm).

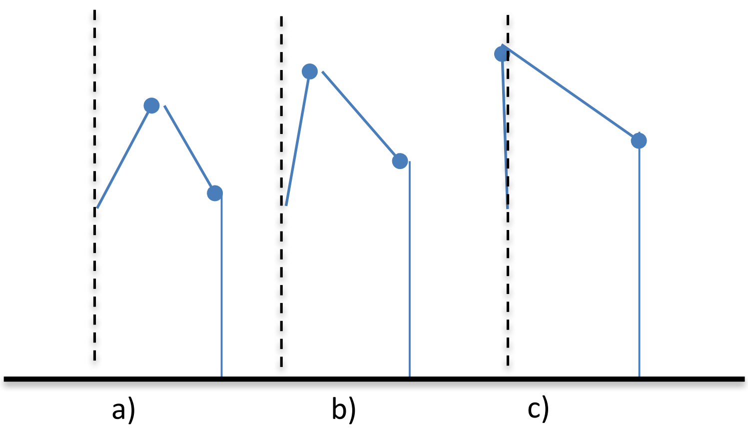
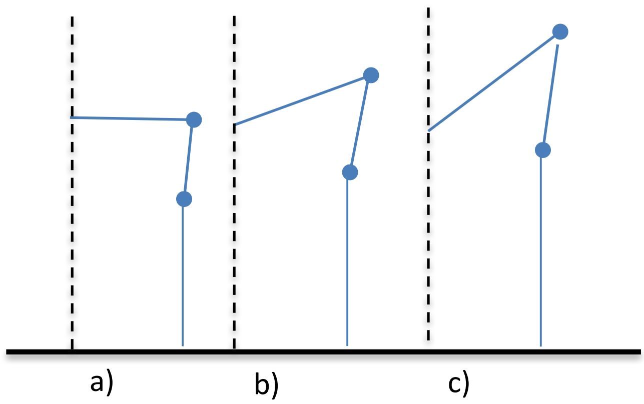


Figure 3-5 Predicted rescuer posture for a short (a), medium (b) and tall (c) rescuer at the lowest platform height (48 cm).

Predicted RAB

The geometric model predicted a curvilinear relationship for RAB for the three rescuers (Figure 3-4). As platform height increased, RAB decreased. At taller platform heights (88-98 cm), RAB converged and presented negative angles. Therefore the model predicted, irrespective of rescuer height, at 88 cm and above, all rescuers would adopt a hyperextended posture i.e. shoulders posterior to hips, (Figure 3-6) or vertical posture. Also at 98 cm, RAB began to increase, for the short rescuer, and was closer to zero than the taller rescuers.

Figure 3-6 Predicted rescuer posture for a short, medium and tall rescuer at the tallest platform height (98 cm), demonstrating hyperextension of the rescuer's back.



3.2.3 Summary of Geometrical Model

The geometrical model predicted RAA and RAB in relation to a manikin during a simulated in-hospital cardiac arrest. The model presented RAA and RAB for each rescuer for three different heights within British Standards for medical platforms[93].

3.3 Method

3.3.1 Volunteer Recruitment

Ethical approval was necessary was this experiment and granted by the Faculty of Medicine Ethics Committee (Appendix E) on 7th October 2010 (Ref RGO 7567).
Recruitment posters were placed around an acute NHS Trust. Potential volunteers contacted the author for further details of the experiment. Each participant received a participant information sheet (appendix C) and completed a consent form (appendix B). Volunteers were excluded if they had not completed a BLS course approved by the Resuscitation Council (UK) within 12 months or if volunteers reported musculo-skeletal injuries. All participants were healthcare professionals working in an acute NHS trust. Twenty-two BLS trained volunteers (n=22) were recruited onto the experiment.

3.3.2 Procedure

Rescuers were stood adjacent to the platform at a distance of 45 cm from the centre of the manikin's chest. Rescuers were instructed to adopt a posture to perform BLS for a clinical range of randomised platform heights (48, 58, 68, 78, 88 and 98 cm). Heights refer to the top of the hospital platform and the platform was non-compliant.

BLS comprised of 30 chest compressions and 2 rescue breaths. Rescue breaths were not delivered but counted by the rescuer to replicate resuscitation practice. Each volunteer performed 2 cycles of BLS at a rate of 100 bpm[36]. Rescuers were blinded as to the height of the platform during BLS and were not provided with feedback on the quality of their performance. Rescuers were provided with a metronome to achieve the correct rate for the delivery of chest compressions.

Please note at the time of this trial the 2005 resuscitation guidelines were current.

3.3.3 Instrumented Manikin

A commercial manikin (Laerdal™) was modified (Figure 3-7) to present rescuers with a chest compliance similar to the adult human chest[77,124]. The manikin's chest characteristics were calibrated prior to and on completion of the study (chapter 2). A chest compliance of 7.5 N/mm was recorded. Depth of chest compression at different platform heights was recorded from the instrumented manikin using the Labview CPRVI (V5.1 National Instruments) for all rescuers.

Figure 3-7 Instrumented manikin positioned on a medical platform (lateral view**).**

Manikin Data Analysis

Data derived from the instrumented manikin was detected and sampled at the peak of the waveform to obtain the depth compression and troughs to record the residual compression. The peaks and troughs were sampled over the 60 chest compressions (2 x 30 compressions) and a mean and standard deviation were obtained for each rescuer at each platform height.

3.3.4 Geometrical Data Measurement

The CODA[128,131] (Codamotion: Charnwood Dynamics Ltd Version 5.46) system was used to record the position of key rescuer anatomical landmarks to enable the measurement of RAA and RAB (chapter 2). Eight active markers (infra-red) were placed in key locations: Spine – C5, shoulder – lateral edge of acromion, elbow – lateral epicondyle, hand – ulna styloid process, lateral head of 5^{th} hip – greater trochanter, knee, ankle – lateral malleolus and foot (

Figure 3-8). The CODA system with the markers identified permitted a 2D image of rescuer posture to be visualised (

Figure 3-8). An additional marker was placed to identify the height of the platform in relation to the rescuer. RAA and RAB were measured for each rescuer at each platform height.

The study was conducted at the Gait Laboratory, University of Southampton.

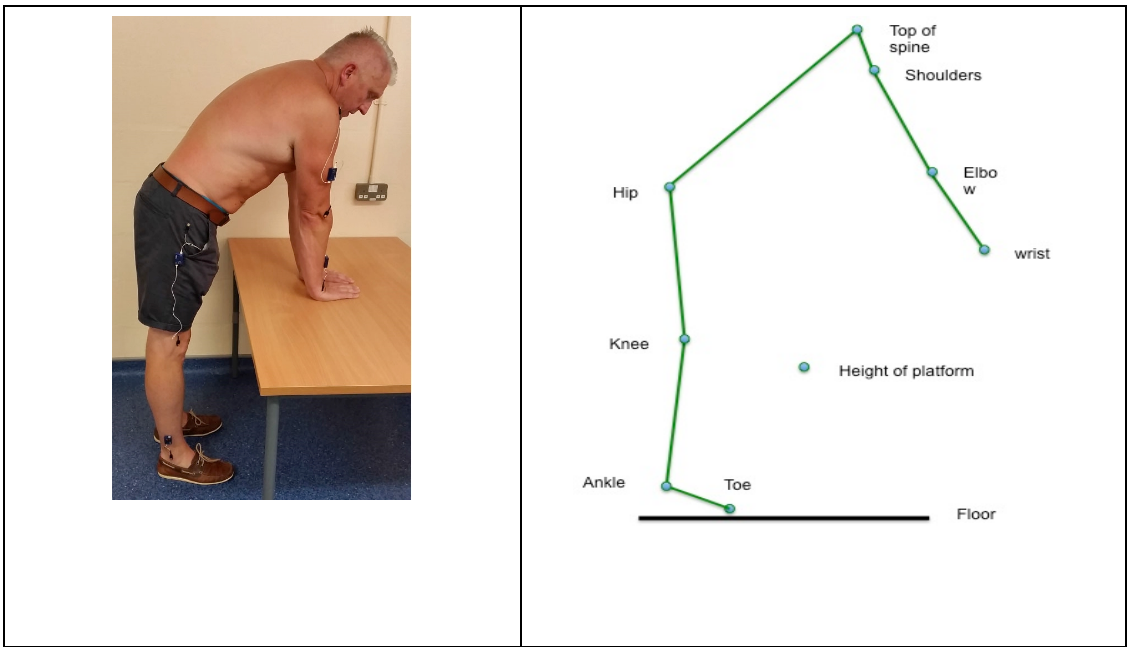


Figure 3-8 CODA motion markers in position on rescuer (left). The CODA derived rescuer image (right) positioned at platform height 48 cm**.**

3.3.5 Sample Size

A power calculation was necessary to determine the appropriate sample size required to detect a statistically significant difference in depth of compression between platform heights. A preliminary pilot study of 5 volunteers at different rescuer postures was conducted. The pilot study revealed a difference in depth of compression of 6.33mm (SD 2.4) between the required rescuer posture (RAA = 0°) and sub-optimal posture (RAA > 30°), representing a higher platform height. Accepting a significance level of 0.01 and a power of 80%, a sample size of 19 was calculated. It was intended to recruit 25 subjects. This exceeds the prescribed number and would compensate for any attrition or missing values, and was comparable with similar studies[81,84,115].

3.3.6 Statistical Analysis

All data retrieved from the instrumented manikin and Codamotion system were exported into Microsoft Excel (2007) and copied into SPSS. Data analysis was performed using SPSS (IBM) Version 22.

The data collected for the experiment were tested for normality, using depth of compressions, recorded from the instrumented manikin, as the dependent outcome. This determined the appropriate statistical test for analysis. A normally distributed data set required a parametric test, ANOVA, to test for differences in depth of compression across all platform heights. The analysis of variance (ANOVA) is a statistical test for comparing means between more than two groups (normal distribution). Therefore, appropriate for comparing the mean depth of compression at different platform heights. In addition, the depth of compression achieved by each rescuer at each platform height permitted the rescuers to be considered as their own control group i.e. matched depth of compression across the range of platform heights.

3.3.7 Analysis of Geometrical Model

To evaluate the accuracy of the novel geometrical model the Bland-Altman[132] method was performed on the data set. A Bland-Altman method is used to compare two quantitative measurements to establish the precision of the model by comparing the averages and differences between measurements with limits of agreement set at 95%. The data sets are predicted and measured rescuer angles (RAA and RAB). Bland-Altman analysis was performed with SPSS (IBM) Version 22.

3.3.8 Multivariate Analysis

Multivariate analysis permits the interpretation of confounding variables within the rescue population. For this study; platform and rescuer height were considered as variables and regression analysis identified the most significant variable related to the quality of chest compressions.

3.4 Results

3.4.1 Rescuer Demographics

Twenty-two BLS trained volunteers (10 female and 12 male) with a mean age of 30.2 years (SD 8.5) years participated in the experiment. The mean height of the rescuers was 1.76 m (SD 0.12) and mean weight 72.2 Kg (SD 16.3) (Table 6).

Table 6 Demographic data of the study population.

	Mean	SD	Range	n
Age (years)	30.2	8.5	21.0 – 49.0	22
Height (metres)	1.76	0.12	1.5 - 2.0	22
Female	1.65	0.08	1.5 – 1.74	10
Male	1.84	0.07	1.75 – 2.0	12
Weight (Kg)	72.2	16.3	52.0 – 120.0	22
Female	60.2	4.6	52.0 – 67.1	10
Male	82.2	15.8	63.4 – 120.0	12
BMI (Kg/m^2)	23.2	3.3	27.0 – 66.0	22

3.4.2 Analysis of Depth of Compression

Regression Analysis - Platform Height and Rescuer Height

Regression analysis, incorporating rescuer matched, revealed platform height as statistically significant (P<0.001) and rescuer height not statistically significant (P0.077). Modelling with or without rescuer height, platform height demonstrated statistical significance.

Table 7 Regression Analysis

Parameter	Estimate	CI (95%)		P Value
Intercept	-13.88	-60.3	32.6	0.54
Platform Ht 48	16.0	13.6	18.3	0.000
Platform Ht 58	15.6	13.3	18.0	0.000
Platform Ht 68	12.3	10.0	14.7	0.000
Platform Ht 78	9.0	6.7	11.4	0.000
Platform Ht 88	2.6	0.2	5.0	0.000
Platform Ht 98	Ref	Ref	Ref	Ref
Rescuer Ht	23.59	-2.7	49.9	0.077

Regression Formula:

Depth of compression = -13.88 + estimate for platform height + 23.59 x rescuer height (m).

Regression analysis demonstrated rescuer height as not statistically significant despite rescuer height being integral to the model for predicting posture. Further analysis of rescuer height for each platform height is necessary.

Platform Height

The graph below demonstrates the association between platform height and depth of compression (Figure 3-9). As platform height increased the mean depth of compression achieved by 22 BLS trained rescuers decreased. The graph also presents the mean depth of compression (+/-1.96 SEM) at each platform height versus the minimum depth of compression (40 mm) required by the 2005 resuscitation guidelines[36] current at the time of the experiment. At platform heights higher than 68 cm, rescuers were unable to deliver appropriate resuscitation treatment.

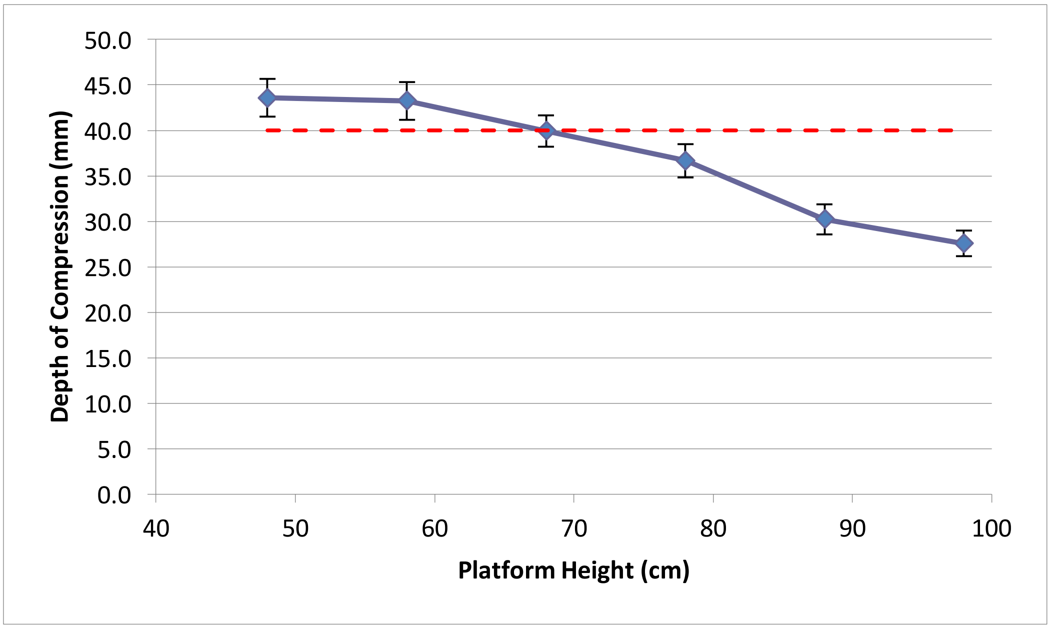


Figure 3-9 A line graph demonstrating the association between platform height and depth of compression (+/=1.96 SEM) and the minimum depth of compression (red dotted line). n22

An adjusted ANOVA test was used to compare the differences between the mean depths of compression achieved at different platform heights matched for each rescuer (Table 8).

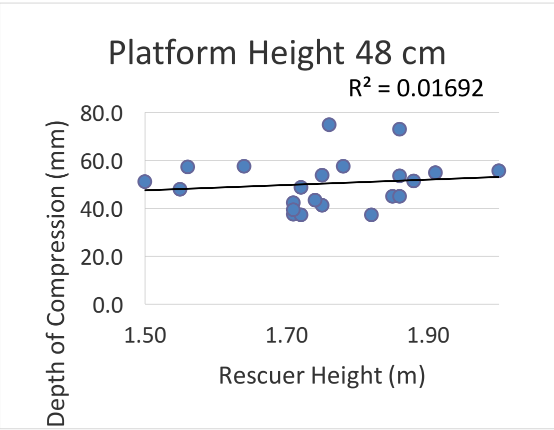
Table 8 Summary of Least Significant Difference between platform height (48 cm) and the remaining platform heights using depth of compression.

Platform height (cm)	Mean diff	95% CI	P
58 – 48	0.3	-2.7 to 2.0	0.782
68 – 48	-3.6	-6.0 to -1.2	0.003
78 – 48	-6.9	-9.3 to -4.5	<0.001
88 – 48	-13.3	-15.7 to -10.9	<0.001
98 – 48	-16.0	-18.3 to -13.6	<0.001

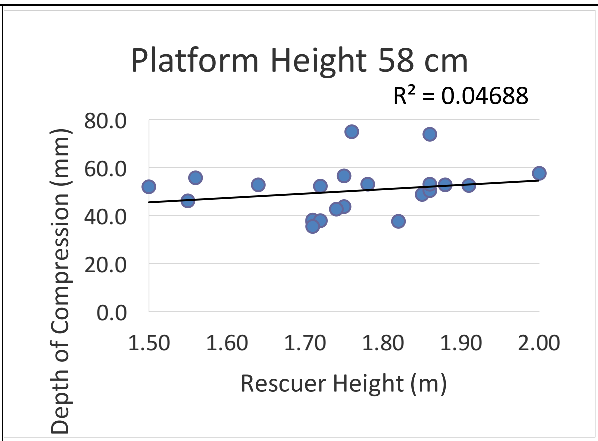
The mean difference in depth of compression, between the lowest platform height (48 cm) and 58 cm did not demonstrate statistical significance. However, comparison of platform heights, 48 cm and 68 cm and above, statistical significance was reached (P=0.003). The mean reduction in depth of compression, at a platform height of 68 cm, was 3.6 mm (-6.0 to -1.2 mm, 95% CI). With further reduction in depth of compression with increasing platform height, peaking at 16 mm (-18.3 to -13.6, 95% CI) at the highest platform height (98 cm).

Rescuer Height

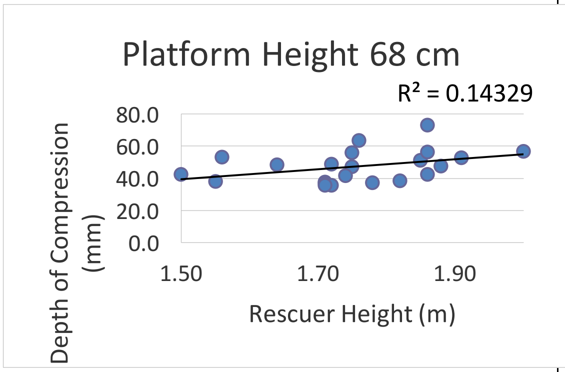
Correlation between rescuer height and depth of compression for each platform height are presented in Figure 3-10. At the lower platform height (48-68 cm) no significant a correlation of was demonstrated between rescuer height and depth of compression. However, the levels of correlation increased with increasing platform height. At platform height 78 cm, 36% of the depth of compression achieved can be attributed to rescuer height (P=0.01). At the tallest platform height (98 cm) a maximum positive correlation of 43% (P=0.001) was demonstrated. Increasing levels of correlation suggest rescuer height became more important at taller platforms (78 – 98 cm). This change in correlation could account for the non-statistical significance for rescuer height previously mentioned with regression analysis (Table 7).



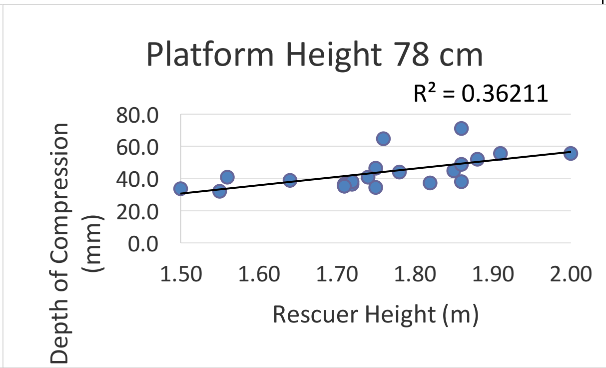
a. Rescuer height versus doc (P=0.70)



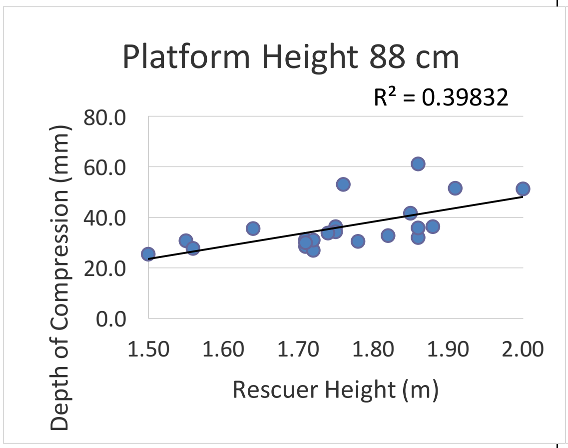
b. Rescuer height versus doc (P=0.53)



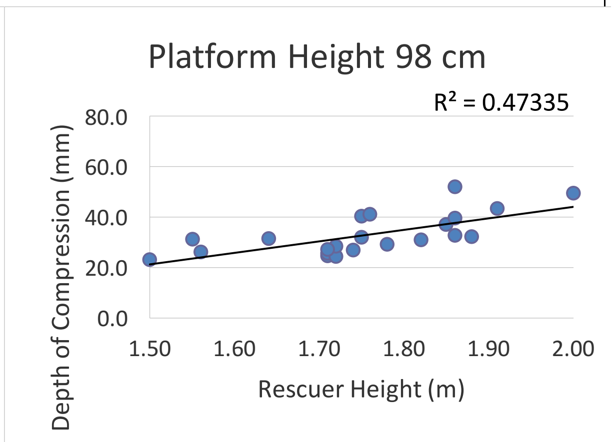
c. Rescuer height versus doc (P=0.24)



d. Rescuer height versus doc (P=0.01)



e. Rescuer height versus doc (P=0.003)



f. Rescuer height versus doc (P=0.001)

Figure 3-10 (a-f) Scatter plots demonstrating correlation between rescuer height and depth of compression for each platform height.

Quality of Rescue Attempts

The rescue cohort (10 females and 12 males) demonstrated the effects of platform height on the quality of rescue attempts for the rescue population. As platform height increased the number of rescuers achieving the minimum depth of compression, recommended by the 2005 guidelines[36], decreased. At the lowest platform (48 cm), 63% of all rescuers achieved the minimum depth of compression. Within this group, 90% were male rescuers. In contrast 42% of female rescuers were considered to be achieving guidelines. The trend between genders continued until at 78 cm and above, female rescuers were unable to compress the manikin's chest to the required depth (40 mm).

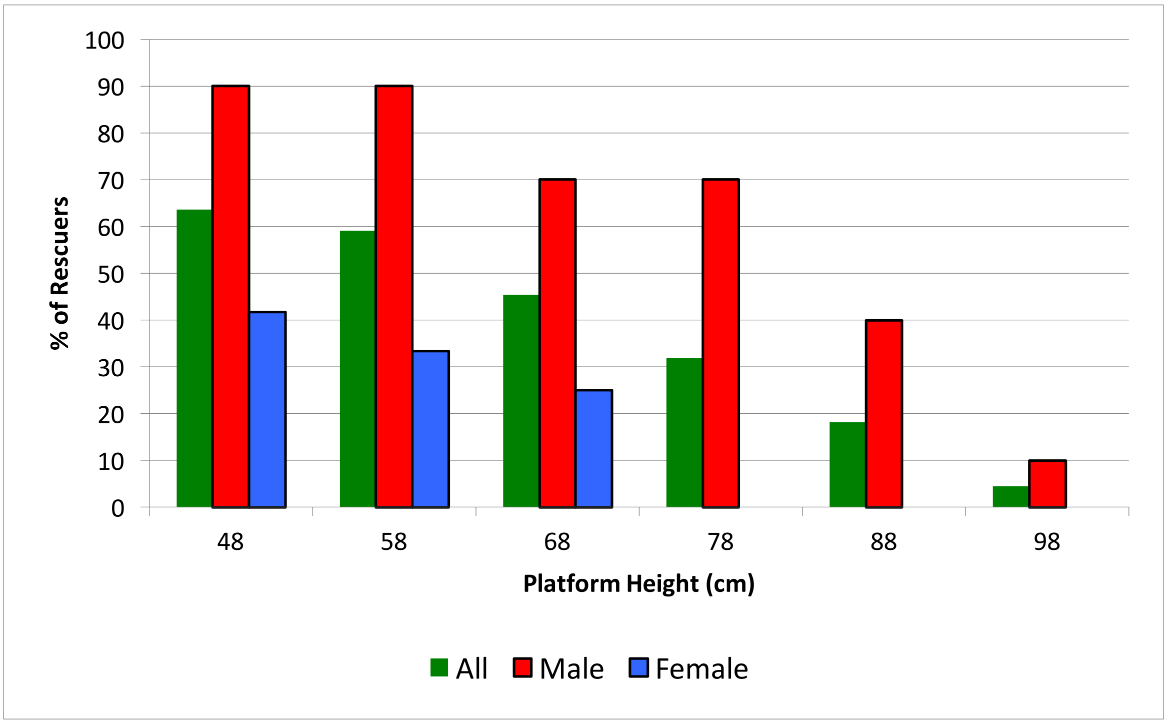


Figure 3-11 A bar chart demonstrating the effect of platform height on the successful delivery of chest compressions by gender.

3.4.3 Rescuer Posture

Platform Height and Rescuer Posture

To determine the measured effect of platform height on the rescuer posture, RAA and RAB were recorded for each rescuer at each platform height. The means of measured angles for all rescuers at each platform height are presented (+/- 1.96 SEM) (Figure 3-12).

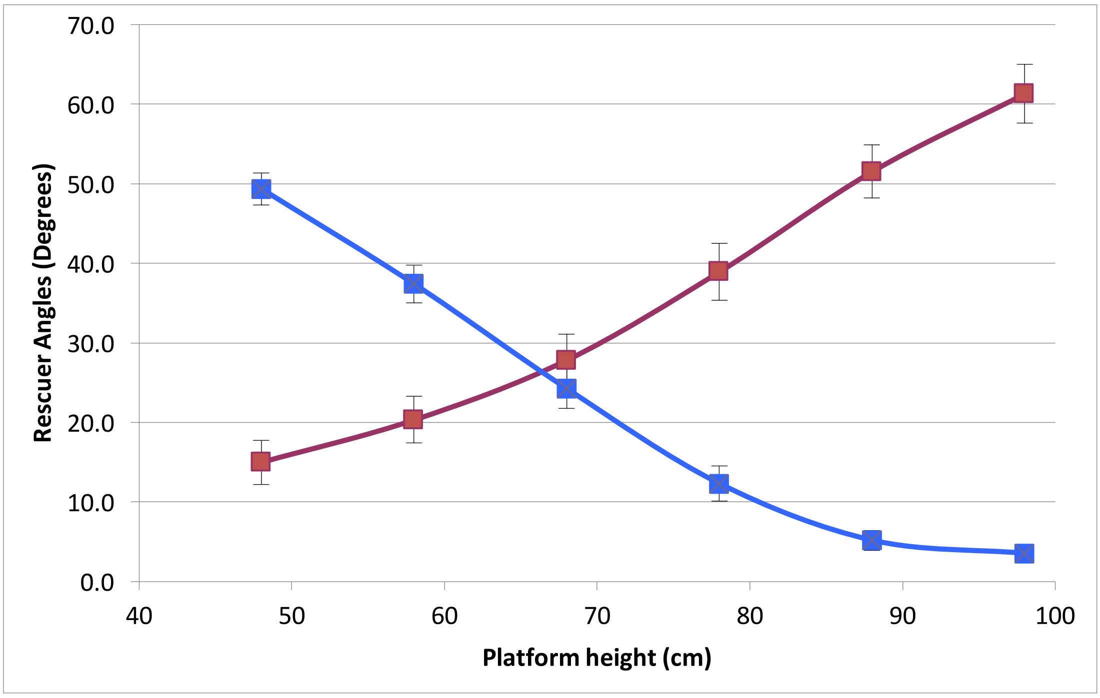


Figure 3-12 A line graph presenting the mean measured angles RAA (red line) & RAB (blue line) for the rescue population at each platform height (+/- 1.96 SEM). n22.

Figure 3-12 demonstrates at the lowest platform height (48 cm), collectively rescuers did not position their shoulders (RAA) vertically above the manikin's chest, as per the predicted model (

Figure 3-5). As platform height increased, collectively rescuers' shoulders were displaced further from the manikin's midline and failed to achieve published postural recommendations[19,36].

At the lower heights, a larger change in RAB was demonstrated than at the taller heights. Increasing platform height demonstrated reduced levels of rescuer upper body flexion as rescuers became more vertical in their posture. However, there is no evidence of rescuer hyperextension as predicted by the model (Figure 3-4).

Rescuer Posture

2D images of rescuer posture created by CODA infra-red markers (Figure 3-13), present a rescuer of average height (1.76 m), at three different platform heights (48, 78 and 98 cm). The lowest platform height demonstrates rescuer shoulders are (blue dotted line) not vertically above the victim's chest, contravening resuscitation guidelines[19,111]. However, rescuer arms are straight. At 78 cm, the rescuer's shoulders are displaced further from the midline and there is marginal flexion at the elbow joint (b arrow)). At the tallest platform height (98 cm): the rescuer back is almost vertical, arms are flexed at the elbow joint (c arrow) and the rescuer's forearm is predominately in a horizontal plane. The corresponding predicted rescuer posture are presented below the CODA images.

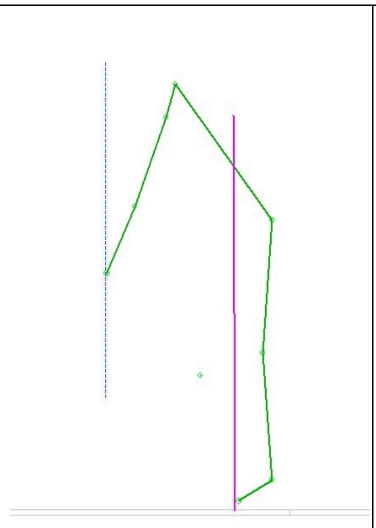
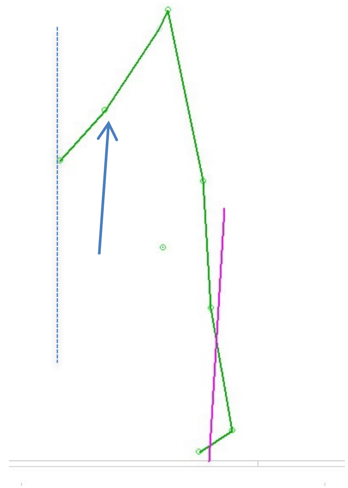
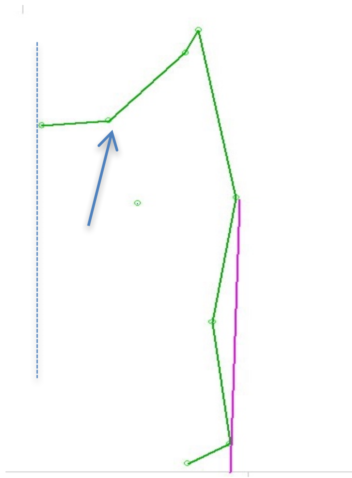
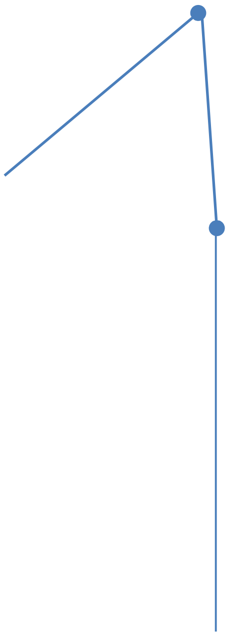
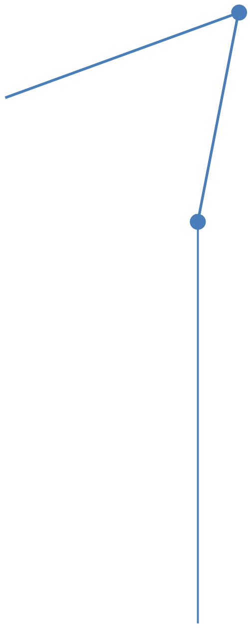
		
a) CODA (48 cm)	b) CODA (78 cm)	c) CODA (98 cm)
		
a) Model (48 cm)	b) Model (78 cm)	c) Model (98 cm)

Figure 3-13 CODA images of a rescuer (1.76 m) at three different platform heights (top) and the corresponding predicted rescuer posture (bottom).

The CODA images (Figure 3-13) revealed flexion at the elbow. The magnitude of elbow flexion was determined by the distance between rescuer shoulder and hand. Figure 3-14 presents the mean change in elbow flexion in relation to the angle of the rescuers back. As platform height increased, RAB decreased and elbow flexion increased.

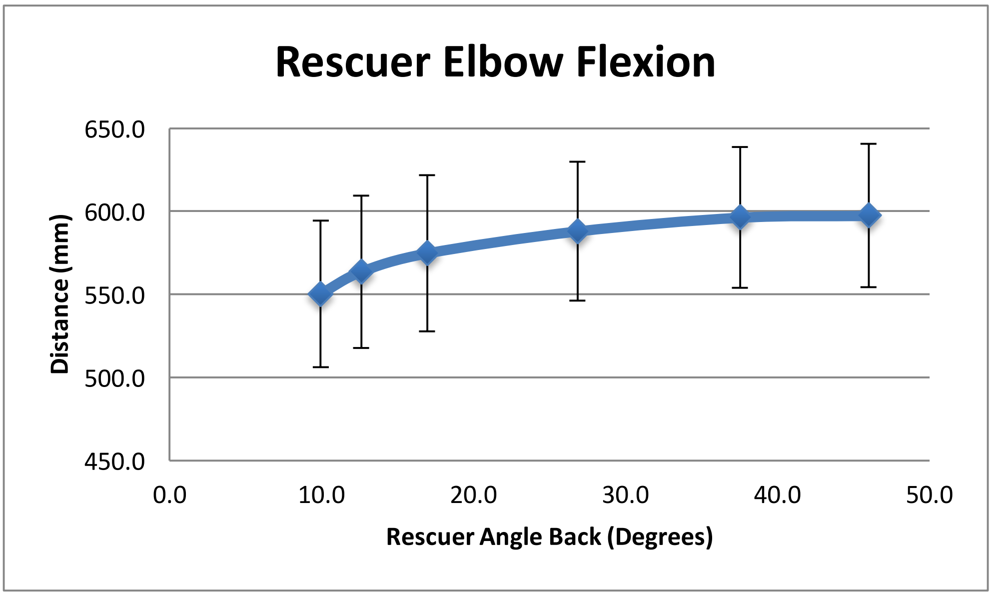


Figure 3-14 A line graph demonstrating the mean distance of rescuer elbow flexion (SD). n22. As RAB increased, elbow flexion increased.

The effects of rescuer height on elbow flexion is presented in figure 3.15. The magnitude of elbow flexion is related to rescuer height; as taller rescuers have longer arms. Shorter rescuers demonstrated elbow flexion earlier than the taller rescuers.

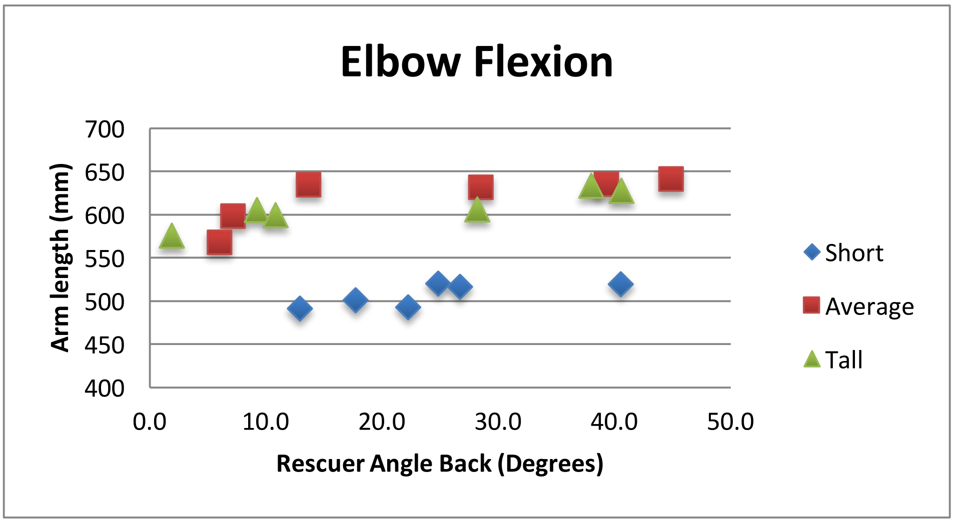
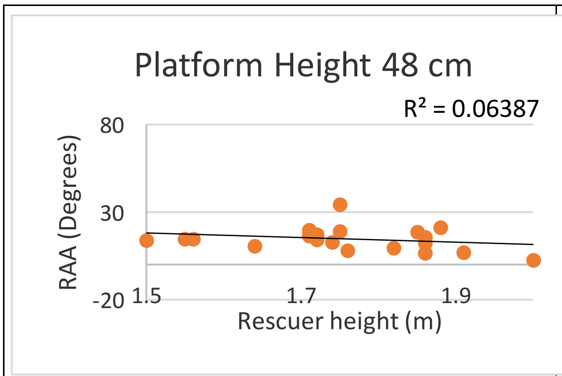


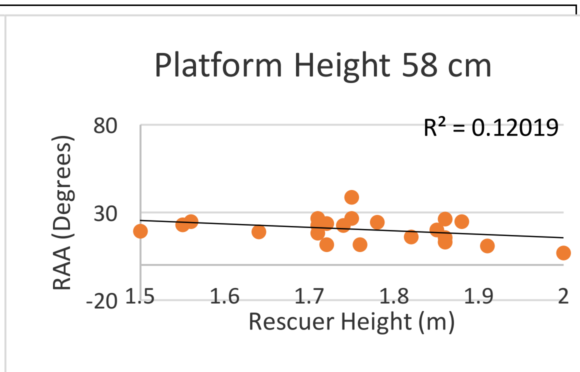
Figure 3-15 A line graph demonstrating elbow flexion for a short, average and tall rescuer.

Rescuer Height – Measured RAA and RAB

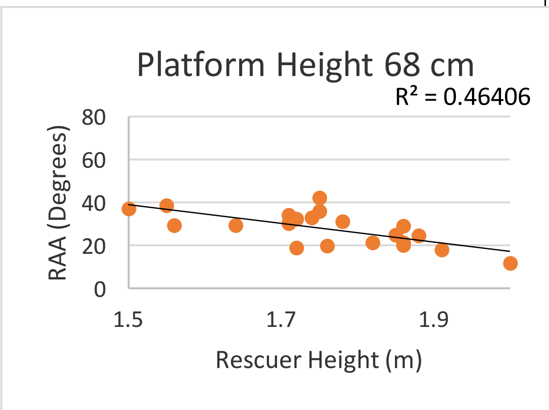
To determine the effect of rescuer height on RAA, rescuer shoulder angles were plotted for each individual rescuer at each platform height (Figure 3-16).



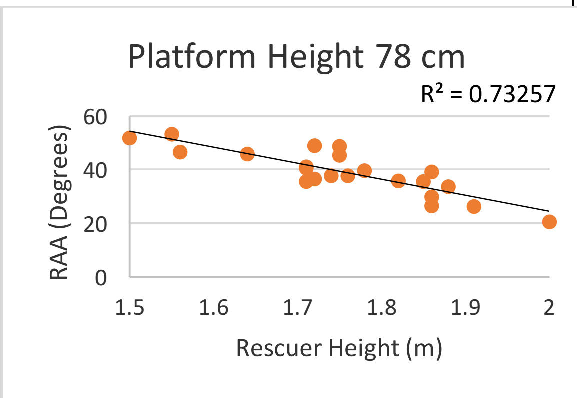
a. Rescuer height versus RAA (P=0.29)



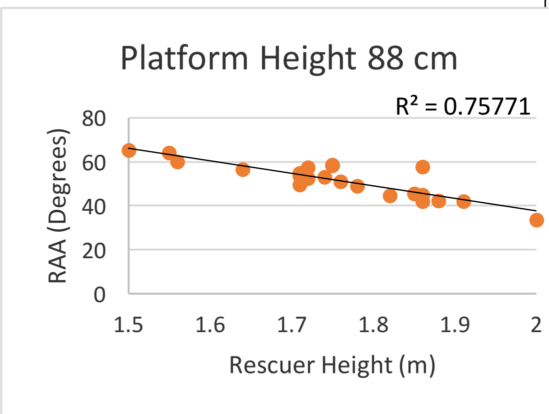
b. Rescuer height versus RAA (P=0.11)



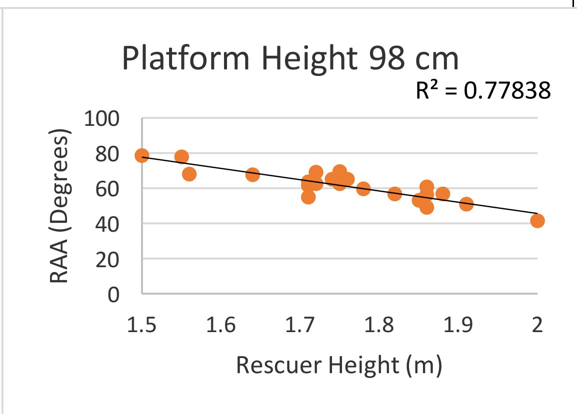
c. Rescuer height versus RAA (p<0.01)



d. Rescuer height versus RAA (P<0.01)



e. Rescuer height versus RAA (P<0.01)

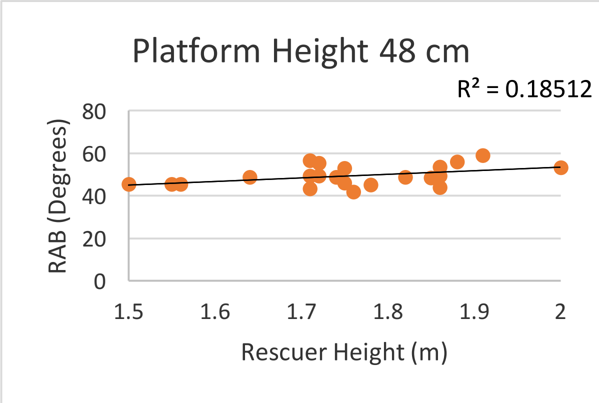


f. Rescuer height versus RAA (P<0.01)

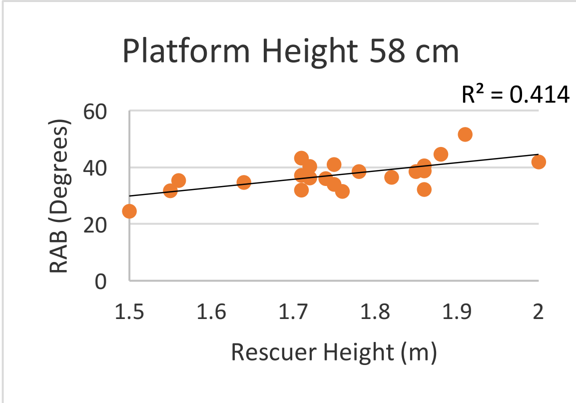
Figure 3-16 (a-f) A scatter plot of correlation between rescuer height and RAA at each platform height.

Figure 3-16 (a-f) demonstrates the relationship between rescuer height and RAA for each platform height. Overall there is a negative correlation between rescuer height and RAA. At the lower platform heights (48 -58 cm) there is an association of 6 -12%. However, this level of correlation was not statistically significant (P=0.29, P=0.11). As platform height increased, the strength of the negative correlation increased. At platform height 68 cm and above there is a statistically significant correlation between rescuer height and RAA. A maximum correlation of 77% for RAA at a platform height of 98 cm is demonstrated (P<0.01). Therefore, as platform height increased, rescuer height becomes more significant for RAA.

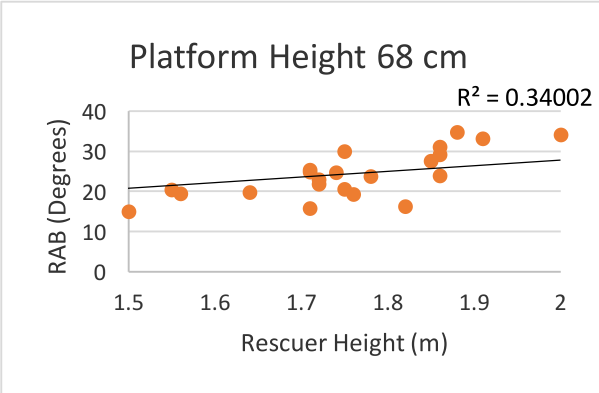
To determine the effect of rescuer height on RAB, rescuer back angles were plotted for each individual rescuer at each platform height (Figure 3-17).



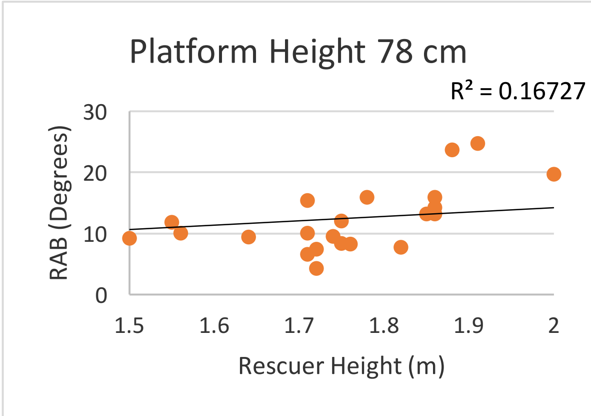
a. Rescuer height versus RAB (P=0.04)



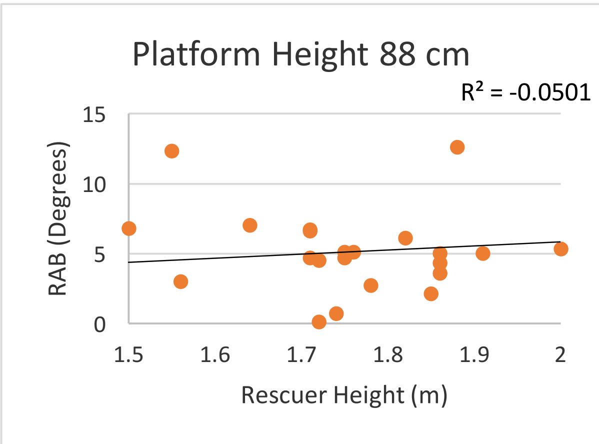
b. Rescuer height versus RAB (P<0.01)



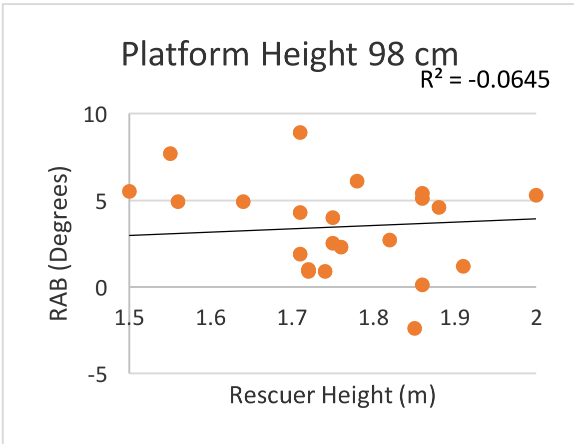
c. Rescuer height versus RAB (P<0.01)



d. Rescuer height versus RAB (P<0.01)



e. Rescuer height versus RAB (P=0.50)



f. Rescuer height versus RAB (P=0.16)

Figure 3-17 (a-f) Scatter plots demonstrating correlation between rescuer height and RAB for each platform height.

Figure 3-17 (a-f) demonstrates the relationship between rescuer height and RAB for each platform height. At platform heights (48 - 68 cm) there is an increasing positive correlation between rescuer height and RAB. As platform height increased, the strength of the correlation increased to a maximum of 34% at platform height 68 cm (P<0.01). However, at platform heights of 78 cm and above the degree of correlation decreased. It is noted from the CODA images (Figure 3-13), rescuers demonstrated marginal elbow flexion at 78 cm and above. This altered geometry would impact on the level of correlation between these parameters as the model did not include elbow flexion.

Rescuer Angle Arm and Depth of Compression

The correlation between the mean position of the rescuer shoulders (RAA) and the mean depth of compression is presented below (Figure 3-18). Statistical significance for depth of compression was reached at a platform height of 68 cm. This platform height corresponds with a mean RAA of 27.8° (SD 7.8) and is associated with a mean depth of compression of 39.9 mm (SD 7.9). The graph also demonstrates increasing RAA is associated with reduced depth of compression. The minimum depth of compression is presented (red line).

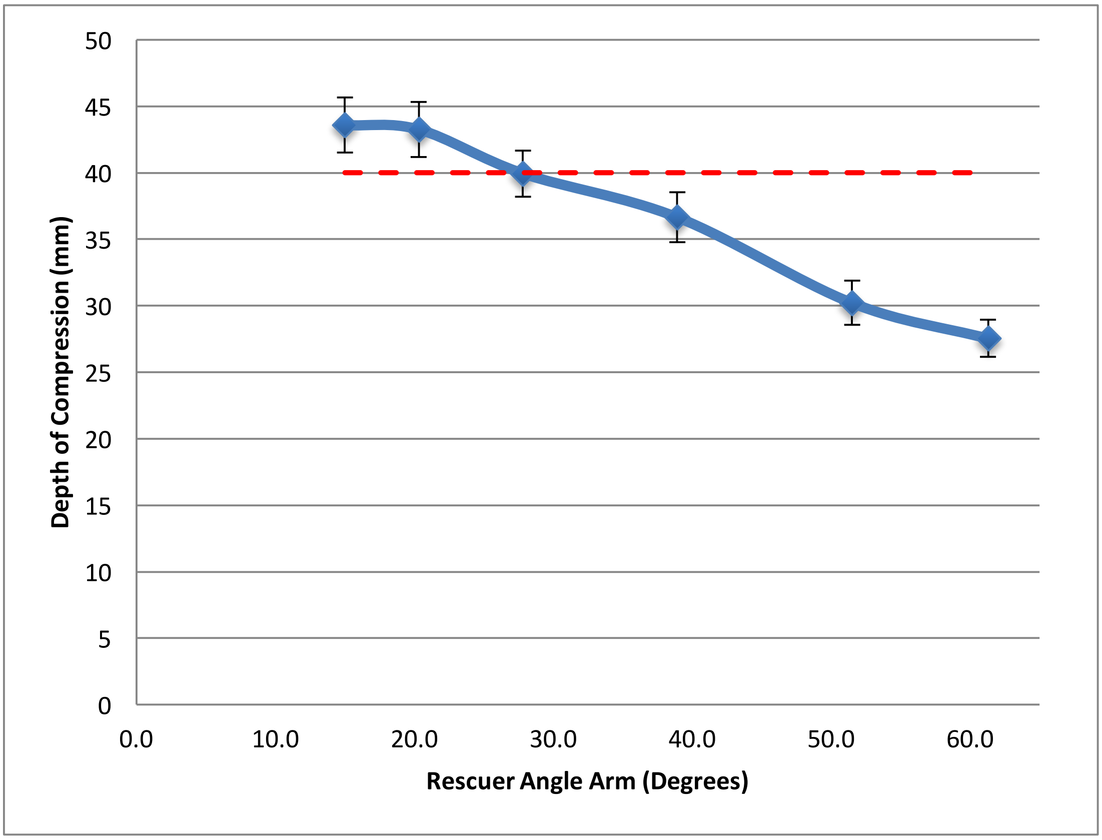


Figure 3-18 A line graph presenting the correlation between mean RAA (+/-1.96 SEM) and required depth of compression[36] (red dashed line).

3.4.4 Evaluation of Geometrical Model - Platform Height (RAA and RAB)

At each given platform height, the height of each individual rescuer was entered into the model to calculate RAA and RAB. From these rescuers matched heights a mean RAA and RAB was calculated for each platform height. The mean predicted and mean measured, rescuer matched RAA and RAB for each platform height, are presented graphically in Figure 3-19 and tabulated in table 9 and 10, respectively.

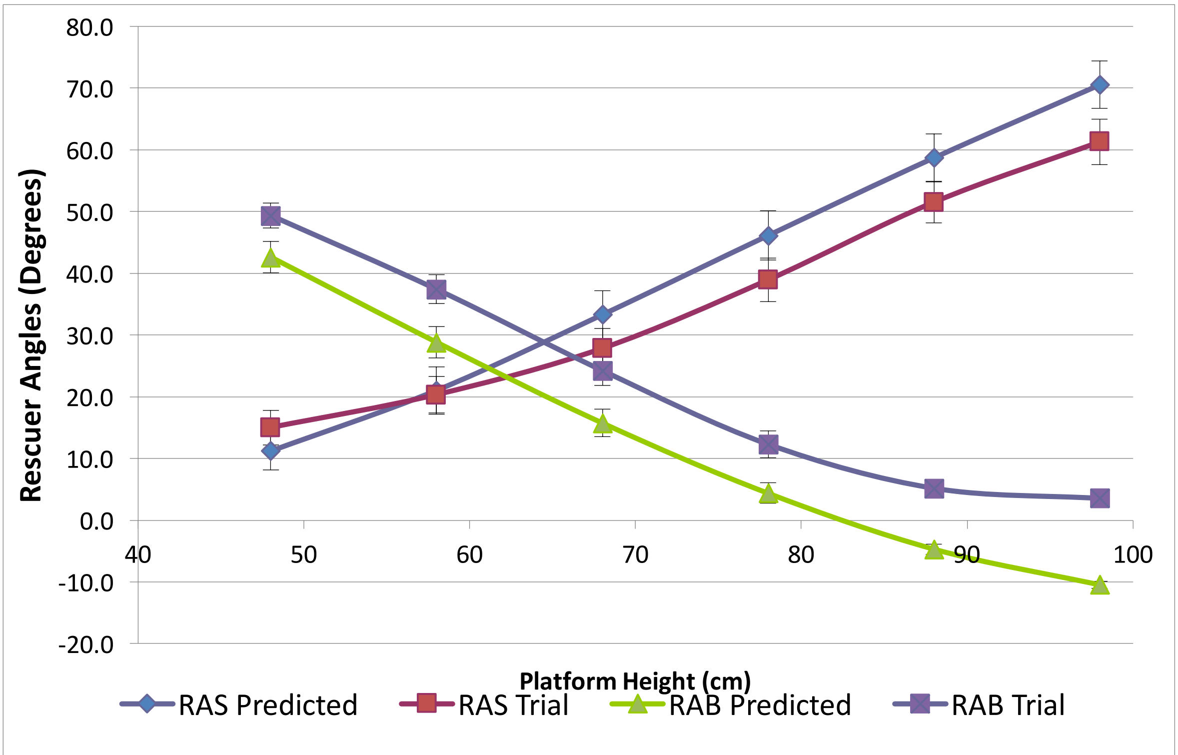


Figure 3-19 A line graph presenting the mean predicted and mean measured rescuer angles (RAA & RAB) across a range of platform heights (+/-1.96 SEM) n22.

Table 9 Predicted and measured means (SD) for RAA at each platform height for all rescuers (n=22).

RAA	48 cm	58 cm	68 cm	78 cm	88 cm	98 cm
Predicted	11.2° (7.3)	21.3° (9.2)	33.3° (9.4)	46.1° (9.5)	58.7° (9.4)	70.5° (9.2)
Measured	15.0° (6.6)	20.3° (7.0)	27.8° (7.7)	38.9° (8.5)	51.5° (8.0)	61.3° (8.8)

Table 10 The predicted and measured means (SD) for RAB at each platform height for all rescuers (n=22).

RAB	48 cm	58 cm	68 cm	78 cm	88 cm	98 cm
Predicted	42.6° (6.1)	28.8°(6.0)	15.7° (5.4)	4.4° (4.0)	-4.7° (2.0)	-10.5°(1.4)
Measured	49.4° (4.8)	37.4° (5.6)	24.2° (5.9)	12.3° (5.3)	5.2° (3.0)	3.5° (2.7)

The geometrical model correctly predicted the inverse relationship between the rescuers shoulders (RAA) and back (RAB). The mean measured values follow a near linear pattern as the mean of the predicted values across all platform heights.

Individually, the geometrical model and assumptions previously described (section 3.1.1), predicted values for rescuer shoulders (RAA) and back (RAB) for a short (1.5 m), medium height (1.76 m) and tall (2.0 m) rescuer, across a range of platform heights are presented graphically (Figure 3-4)

The geometrical model predicted as platform height increased, RAA increased with a near linear trend for the three different rescuer heights. At the lowest platform height (48 cm) the model predicted the rescuer shoulders would not be optimally positioned in accordance with resuscitation guidelines[36] for the short and averaged height rescuer. The model predicted the short rescuer shoulders would be 29.9° displaced from the centre of the manikin's chest. The average height rescuer shoulders would be 10.5° off centre, with only the taller rescuer (2.0 m) achieving the published rescuer posture at 48 cm.

At a platform height of 58 cm, the model predicted the taller rescuer would satisfy resuscitation protocol posture. The average height and shorter rescuer shoulders would be displaced further from the centre of the manikin's chest. At platform heights 68 cm and above, rescuers of 1.5 to 2 m would be unable to obtain the recommended rescuer posture.

In contrast, as platform height increased, the model predicted RAB decreased in a near linear trend until the taller platform heights. In addition, the model predicted at platform heights 88 cm and above, RAB becomes a negative value for the shorter rescuers. The model predicted at 88 cm, the taller (2.0 m) rescuer would be stood upright.

Beyond a platform height of 88 cm, the values for these angles became negative. A negative value for RAB would translate into the hyperextension of the rescuer back whilst delivering BLS. Initially, RAB demonstrates a linear relationship for the average height and taller rescuer and then presents a curvilinear characteristic above a platform height of 88 cm for a shorter rescuer.

Rescuer Angle Arms (RAA)

The accuracy of the geometrical model for each platform height, for all rescuers, was evaluated using the Bland-Altman method; rescuer shoulders - RAA – (Table 11) and rescuers back, RAB – (Table 12). The overall mean bias for RAA was 4.3° and RAB -9.2° across all platform and rescuer heights.

Table 11 Mean bias RAA - Rescuer Angle Arm.

Platform Height (cm)	Mean Bias RAA(°)	LLA	ULA
48	-3.8	-21.3	13.7
58	0.7	-17.6	19.0
68	5.5	-8.5	19.0
78	7.2	-2.7	17.0
88	7.2	-2.0	16.3
98	9.2	0.6	17.9

Mean RAA bias with upper and lower limit agreement at 95% (+/- 1.96 SD) n22, LLA lower level agreement, ULA upper level agreement.

The overall mean bias (4.3°) suggests the geometrical model predicted similar angles for RAA, for all rescuers across all platform heights, compared to measured values. However, the mean bias, for specific platform heights increased with increasing platform heights with the largest bias at the tallest platform height (9.2°). However, the difference between the LLA and the ULA suggests a wide range in which the true value could exist for an individual rescuer across all platform heights.

Rescuer Angle Back (RAB)

Overall the mean RAB bias, -9.2°, across all platform heights for all rescuers suggested a good level of agreement between predicted and measured angles. The mean bias for each platform height demonstrated smaller differences between predicted and measured values for RAB (Table 12). The mean RAB bias, gradually increased as platform height increased, peaking at -14.0° at the highest platform height. However, the difference between the LLA and the ULA suggests a wide range in which the true value could exist for an individual rescuer and degrades the reliability of the model.

Table 12 Mean Bias (RAB) - Rescuer Angle Back

Platform Height (cm)	Mean Bias RAB	LLA	ULA
48	-6.2	-17.9	5.5
58	-8.6	-18.4	1.2
68	-8.5	-16.4	-0.6
78	-7.9	-15.7	-0.2
88	-9.9	-16.7	-3.0
98	-14.0	-18.9	-9.1

Mean RAB bias with upper and lower limit agreement at 95%, (+/- 1.96 SD) n22, LLA lower level agreement, ULA upper level agreement.

Rescuer Height

The rescuer height component of the geometrical model was evaluated by plotting the mean differences for RAA across all platform heights (Figure 3-20). Mean differences, between predicted and measured, for RAA demonstrated a negative correlation (R^2 0.456). As rescuer height increased, the differences between the predicted and measured values for RAA decreased. The relationship between mean differences RAA and rescuer height demonstrated a statistical significance (P<0.001).

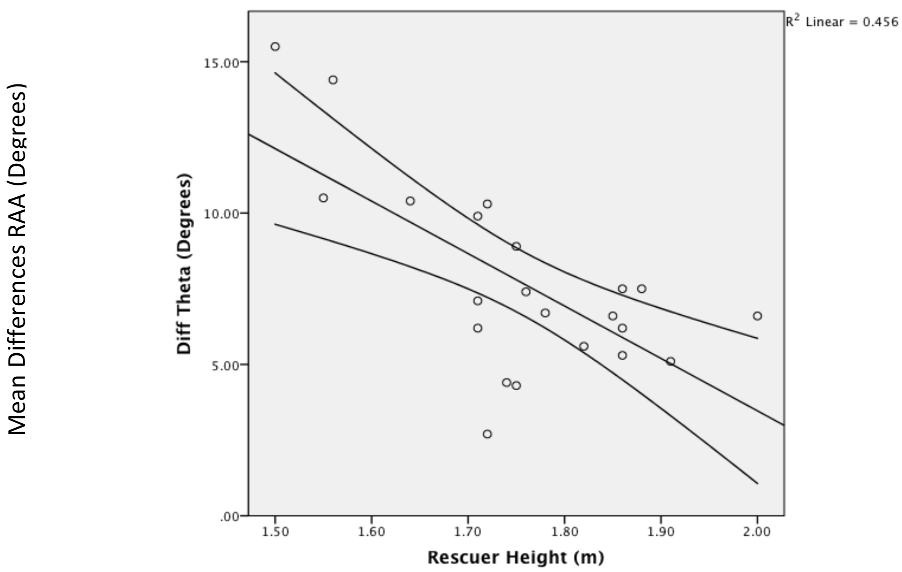


Figure 3-20 A scatter plot demonstrating the mean differences in RAA between predicted and measured values for each rescuer across all platform heights (+/-1,96 SEM)(P<0.001). n22.

The rescuer height component of the geometrical model was evaluated by plotting the mean differences, between predicted and measured RAB, across all platform heights for all rescuers (Figure 3-21). The degree of association demonstrated a negative correlation (R^2 0.332) with a P value of 0.005.

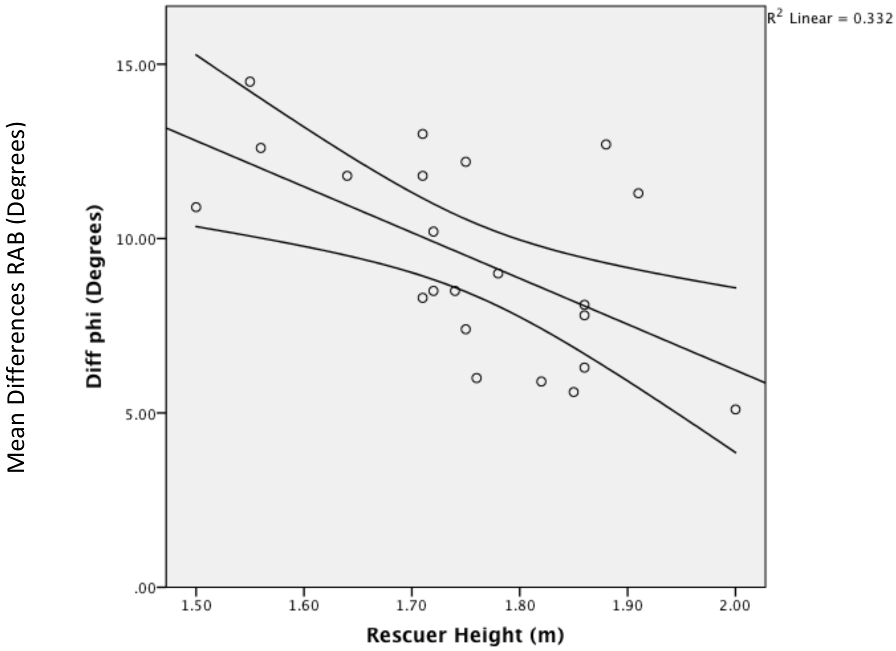


Figure 3-21 A scatter plot demonstrating the mean differences in RAB between predicted and measured values for each rescuer across all platform heights (+/-1.96 SEM)(P=0.005). n22.

3.5 Discussion

This section will outline the key findings of chapter 3 and discuss details of the geometrical model. Further work and limitations of the model will be discussed in chapter 5.

As previously highlighted (section 1.2), resuscitation with a sub-optimal rescuer posture i.e. sub-optimal environment, could occur within the hospital setting under current resuscitation guidelines[18,19,55,98] and British Standards for medical platforms[93]. The experiment demonstrated platform height affects the depth of compression during a simulated in hospital cardiac arrest. As platform height increased: the depth of compression and the number of rescuers achieving the minimum depth of compression, in accordance with resuscitation guidelines, decreased. As platform height increased RAA increased and RAB decreased.

Depth of compression data from the study demonstrated a statistically significant difference at platform height 68 cm. Furthermore, platform height is statistically more significant than rescuer height with respect to the depth of compression. Rescuer height became more important at platform heights >68 cm.

Trained BLS rescuers are vulnerable to Increasing medical platform heights. At the lowest platform height 63% of the rescue population achieved the required depth of compression. The success rate decreased as platform height increased. At the tallest platform height 4.3% of the rescue population achieved published values for quality.

Ineffective chest compressions could be delivered to victims of a cardiac arrest, thereby reducing the probability of survival, whilst in a hospital environment. Depth of compression data indicated platform heights should be positioned at 68 cm or below to allow rescuers to achieve their optimum depth of compression. However, the number of rescuers achieving the required depth of compression was greatest at 48 cm.

The model correctly predicted an inverse relationship between RAA and RAB. The model also predicted the position of the rescuer shoulders (RAA), and back (RAB), collectively and individually, across a range of clinically relevant platform heights.

3.5.1 Geometrical Model – Platform height

The geometrical model predicted similar values for RAA and RAB to measured angles, across a range of clinically relevant platform heights (Table 5 and 6, figure 3-19) using rescuer matched heights. The model correctly predicted an inverse relationship between RAA and RAB. Collectively, for all rescuers and across all platform heights, the geometrical model predicted a marginal overestimation of 4.3° across a range of RAA of 60.5°.

In contrast overall the model predicted an underestimation of -9.2° across a range of RAB 45° demonstrating a larger error in range of values. In addition, the predicted mean RAB at platform heights 88 and 98 cm, for all rescuers, produced negative angles. This is in contrast to measured angles and observations from CODA data (Figure 3-13). Analysis of predicted RAB, predominately, revealed negative angles apart from one tall rescuer, (2.0 m) at platform height 88 cm. At platform height 98 cm, all predicted angles for RAB for all rescuers were negative. Negative RAB back angles would suggest rescuers backs were hyperextended during BLS.

CODA images did not reveal hyperextension of the rescuer's back (Figure 3-22). Rescuer arms had undergone flexion. Movement at the elbow joint would therefore shorten the distance between the rescuer shoulders and the manikin and prevent hyperextension of the upper body. It is anticipated and further work required; rescuers of shorter stature would experience flexion at the elbow at lower platform heights than experienced by taller rescuers.

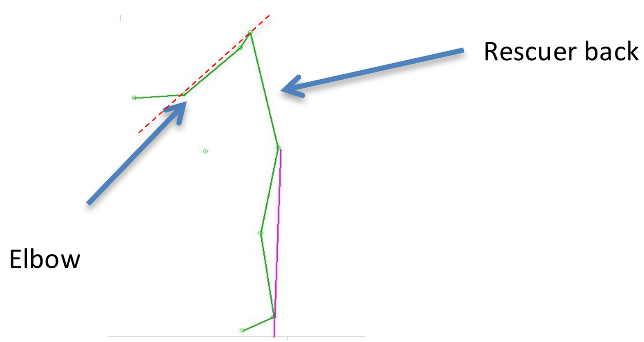


Figure 3-22 CODA image of a rescuer performing chest compressions at platform height 98 cm. Rescuer back is not hyperextended but the arm is flexed at the elbow.

Consideration of the model's assumptions: horizontal distance between the rescuer and victim is constant and the rescuer arms remained straight, would suggest the rescuer had altered their upper body geometry to prevent an unstable, hyperextended posture and therefore invalidate the model. In addition, negatively predicted angles derived from the geometrical model would impact on the mean bias offset and levels of agreement between the data sets for RAB, in particular -9.2°.

Further analysis of the model for each given platform height revealed more specific mean bias for RAA (Table 11) and RAB (Table 12). These corrections could be applied to reduce errors, increase accuracy, in predicting rescuer posture for a rescue population. However, the wide range levels of agreement for RAA and RAB, at each platform height, indicates the geometrical model is not as accurate for individual rescuers as it is collectively and suggests further work is required.

3.5.2 Geometrical Model – Rescuer Height

The geometrical model considered rescuer height for predicting RAA and RAB. The mean differences between predicted and measured angles across all platform heights for each rescuer height are presented in figures 3-21 and 3-22.

The mean differences for RAA suggest the model was a better predictor for the taller rescuer than the shorter rescuer ($P<0.001$). In addition, the level of correlation between the two variables suggests that 46% of the differences in RAA can be attributed to the rescuer height. This suggests that rescuer height became more important in the geometrical model with taller rescuers. As rescuer height increased the difference between predicted and measured decreased. The overall mean difference for RAB at each rescuer height also revealed the model was a better predictor for taller rescuers ($P=0.005$).

Analysis of rescuer height at specific platform heights revealed, there was no correlation between predicted and measured RAA and at lower platform heights (48 and 58 cm). At heights greater than 58 cm there is a greater degree of correlation between predicted and measured RAA. In contrast, RAB demonstrated a greater correlation between rescuer heights at the lower platform heights than at the taller heights. This could be explained by the negative predicted values of RAB, at taller platform heights, based on the geometrical model. CODA also demonstrated shorter rescuers leaned into the medical platform during the delivery of chest compressions. The leaning action shortened the distance between the rescuer hips and the midline of the manikin's chest and would impact on the geometrical model.

Model summary

Despite the marginal differences between predicted and measured angles, overall the geometrical model has demonstrated the principle of modelling rescuer posture in relation to a medical platform and rescuer height. Further development of the model would improve its accuracy (chapter5).

3.5.3 Conclusion

This chapter demonstrated an association between platform height and depth of compression. At platform height 68 cm and above, a statistically significant reduction in depth of compression was demonstrated. The number of rescuers achieving the minimum depth of compression, decreased as platform height increased. Rescuer height became important at the taller platform heights. Using a platform height below 68 cm would lower the effect of rescuer height and improve the quality of chest compressions

The novel geometrical model correctly predicted the inverse relationship between the angle of the rescuers' shoulders and back. The model demonstrated similar characteristics of rescuer angles to measured data across a range of medical platforms.

The experiment demonstrated platform height, primarily, determined rescuer posture and sub-optimal rescuer posture is associated with poor quality BLS. However, the experiment has not demonstrated why rescuer posture is important or the aetiology of reduced depth of compression. It is proposed; rescuer posture limits the functional anatomy of rescuer and therefore determines the efficacy of life saving treatment. A experiment to consider rescuer forces used to compress a victim's chest, and the impact of poor posture is necessary (chapter 4).

4 An Investigation of the Origin of Forces causing chest compression

Chapter 3 demonstrated medical platform height, predominately, accounted for rescuer posture during a simulated in-hospital cardiac arrest. Sub-optimal rescuer posture is associated with a reduction in the depth of compression and the number of rescuers achieving target depths during Basic Life Support (BLS). Chapter 3 also demonstrated rescuer posture could be predicted for a range of clinically relevant platform heights, using trigonometry and anthropometric data.

This chapter develops the findings of chapter 3 with the introduction of a novel biomechanical concept for delivering chest compressions during a simulated in-hospital cardiac arrest (Figure 4.1). It investigates the origins and contribution of forces used by a rescuer to compress an instrumented resuscitation manikin's chest. It also evaluates the effect of rescuer posture on the contribution and distribution of those forces.

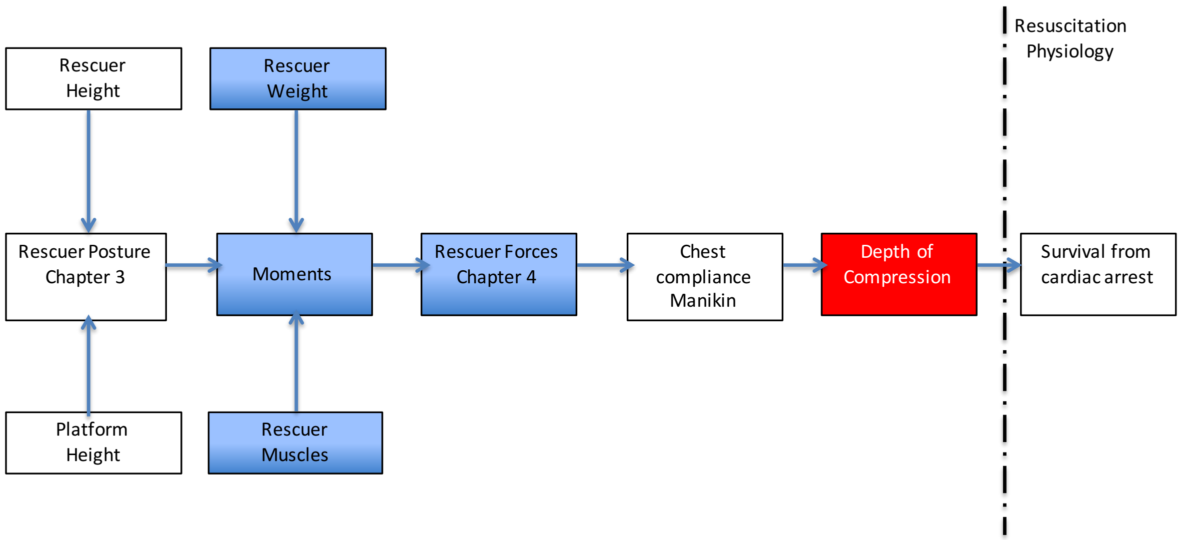


Figure 4-1 Overview of thesis highlighting rescuer forces (blue) and outcome as depth of compression (red).

4.1.1 Aims of Chapter 4

The purpose of this chapter is to present a novel forces concept to identify the origins and contribution of rescuer forces during a simulated in-hospital cardiac arrest. To examine the effects of altered rescuer posture on identified forces.

Aim 1: To determine the contribution of the passive (leaning) component of chest compressions during a simulated cardiac arrest.

Aim 2: To determine contribution of the active (pushing) component of chest compressions during simulated cardiac arrest.

Aim 3: To determine contribution of the dynamic component of chest compressions during simulated cardiac arrest.

Aim 4: To determine the effects of rescuer posture on the forces described and on quality of chest compressions during simulated cardiac arrest.

4.1.2 In-hospital Resuscitation

An in-hospital cardiac arrest is an acute, complex clinical scenario requiring immediate, effective treatment, determined by the Chain of survival (Figure 1-1), to maximise the chances of patient survival and limit neurological problems. The hospital emergency infra-structure activates the cardiac arrest team which is comprised of a variety of healthcare professionals all trained in providing cardiopulmonary resuscitation, and more typically professionals who may have not worked together previously. The team is tasked with providing high quality BLS, administration of drugs and defibrillation of the heart (rhythm dependent). The complexity of the in-hospital cardiac arrest situation will include location within the hospital[27], presenting heart rhythm, time to therapy[133] and more generic factors including time of day, age and gender of the patient[27].

To remove complexity, at a fundamental level and for the purpose of delivering BLS, the in-hospital cardiac arrest scenario presents 1) medical platform 2) a victim and 3) the rescuer. The environment will be determined by the medical platform on which the patient is positioned. The patient will possess adult chest compliance[77] which the rescuer must overcome to compress the chest. Rescuers are equipped with mass, muscles and motion (Figure 4.2). Current guidelines[18,58], require rescuers to compress a patient's chest to 50 mm.

4.2 Theoretical consideration of the origin of Forces

BLS trained rescuers are required to create force to overcome the resistance of the patient's chest[77,79,124,134] in order to compress the chest to the required depth[20,36,58,135]. A force is a push-pull action acting on an object[136]. Potential forces available during an arrest are derived from the physical attributes of the rescuer's body weight i.e. with mass, muscles and momentum. In a static situation the only source of vertical force available to a rescuer is by transferring their body weight onto the patient's chest. An active state, rescuers can engage muscle groups to compress the chest. Finally, in a dynamic situation e.g. during BLS, additional force is achieved by the transfer of angular momentum to the patient's chest as the velocity of the rescuer reduces as peak depth of compression is achieved.

The force due to body weight comprises a passive component and an active component. The passive component of force is achieved by 'leaning' on the patient whilst relaxed thereby transferring a proportion of the rescuers total body weight onto the patient. Additional force may be achieved by recruiting key muscle groups to actively 'push' down onto the patient thereby transferring additional body weight onto the patient.

As the rescuer's body moves during compression, there is a transfer of momentum to the patient which generates additional force. Starting at the beginning of the compression phase, the rescuer is still and therefore momentum is zero. As body weight it transferred onto the patient, so the rescuer develops 'motion', moving forward and downward. As the motion follows an arc, this develops angular momentum which initially grows. As the patient's chest compresses, so the up thrust increases which slows down the motion of the rescuer until at peak depth of compression the rescuer is stationary. It is this braking effect of the patient that converts rescuer momentum into force.

Moments provide a convenient means to model BLS. It was suggested earlier in this thesis that BLS could be modelled by the rotation of two body segments, arms and back each rotating about a fulcrum, the shoulder and hip respectively. At peak depth of compression, the system is instantaneously stationary and hence the up thrust due to the patient's chest is balanced by the force generated from the moments in the rescuer. The remainder of this section will consider how the moments generated by the rescuer are affected by changes in posture.

Moment due to Back

A moment is defined as the product of force and the perpendicular distance between the point a force is applied and the fulcrum[95]. Gravity acts upon the upper body mass (m) to create a force mg. This may be modelled as a force acting vertically downwards applied at the centre of the trunk.

To calculate the moment, the perpendicular distance between the point the force is applied and the hip (D_{HIP}) is required. However, this distance will vary according to the angle of the back (RAB) (Figure 4-2).

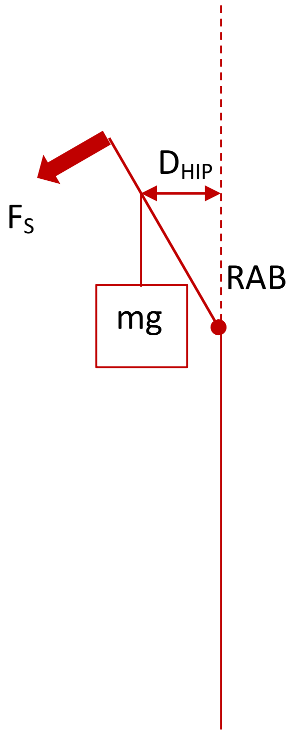


Figure 4-2 – A schematic showing how upper body mass creates a moment about the hip

The moment created by the upper body mass may therefore be calculated as:

$$Back\ moment = mg.back.Sin(RAB) \qquad \text{Equation 15}$$

Where back is the length of the rescuers back measured from the hips to the shoulders.

In addition to the moment created by gravity, the rescuer use their muscles to further increase the moment. However, this additional component is derived from a large number of muscles operating at a variety of angles to the vertical and attaching to bone at different points. An accurate model is extremely complex and beyond the scope of the simple consideration presented in this thesis. Hence the muscular force supplementing the gravitational effect is modelled as an additional vertical force F_M applied at the centre of the upper body.

Having considered the origins of the force and how they change with angle it is now important to consider how this translates into the vertical force applied to the rescuer. The force due to body mass and muscles is conveyed via the shoulders to the patient via the arms. It is therefore possible to calculate how the vertical component of this force changes as the angle of the rescuer's back changes (Figure 4-3).

At peak depth of compression, the rescuer is instantaneously stationary so the moment created by mass and muscles is balanced by the force F_P created by the up thrust of the patient. If this patient force is acts at the shoulders and is always perpendicular to the back, then the perpendicular distance to the fulcrum is always the length of the back.

Therefore:

$$F_P.back \ = mg.back.Sin(RAB) \qquad \text{Equation 16}$$

Or,

$$F_P = mg.Sin(RAB) \qquad \text{Equation 17}$$

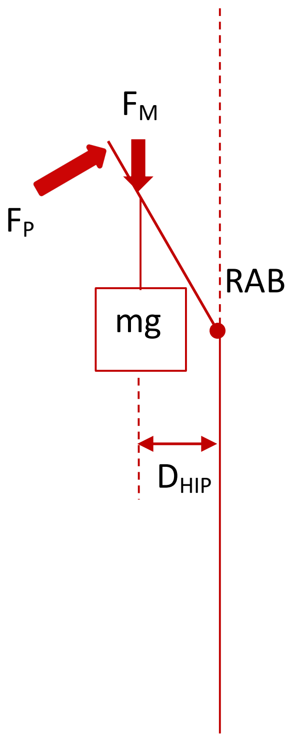
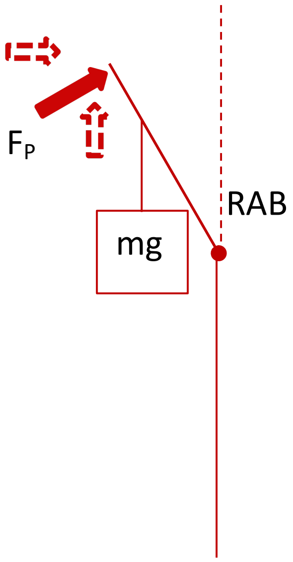


Figure 4-3 Schematic showing how the vertical force alters with RAB.

However, F_P may be thought of as a vertical and horizontal component of force.

So the vertical component can be calculated as:

$F_{VERT} = F_P \text{ Cos } (90 – RAB) = F_P \text{ Sin } (RAB)$ Equation 18



Combining with $F_P = mg.Sin(RAB)$ Equation 17 we get

$$F_{VERT} = mg.Sin^2(RAB)$$ Equation 19

Different height rescuers

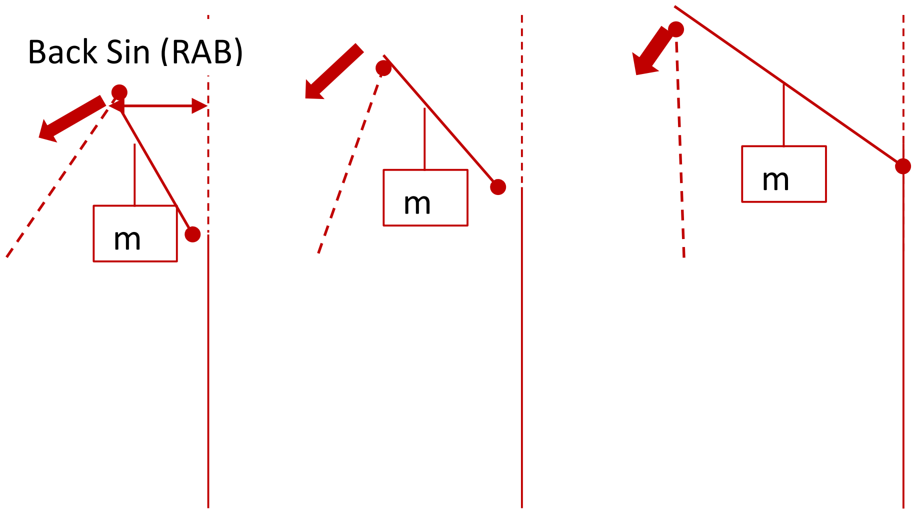
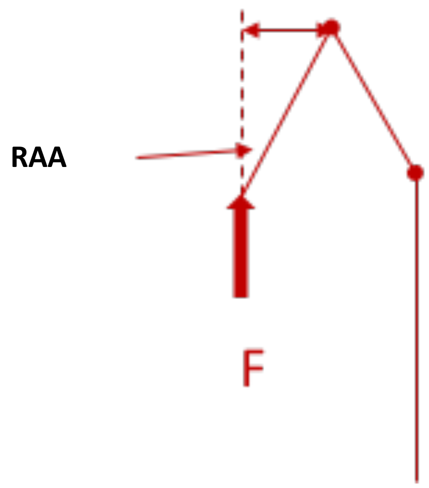


Figure 4-4 2D linear model predictions of back moments for a short, medium and tall rescuer across a range of platform heights. Dotted lines represent rescuer arms.

The magnitude of the back moment is a function of RAB. Therefore, as RAB decreases the static leaning force decreases. A summary of the predictions is presented in Figure 4-7.

4.2.1 Moment about shoulder

As this rescuer presses down on the patient, so the up thrust from the patient's chest creates a moment which is dependent upon the angle of the arm to the vertical. In order to convey the force generated at the shoulders onto the patient, this moment must be opposed. Failure to do so will result in rotatory movement of the arms reducing the depth of compression achieved by the rescuer.



The moment due to the vertical force generated by the patient FP may be calculated as follows:

Arm moment = FP. Sin(RAA) Equation 20

Different height Rescuer

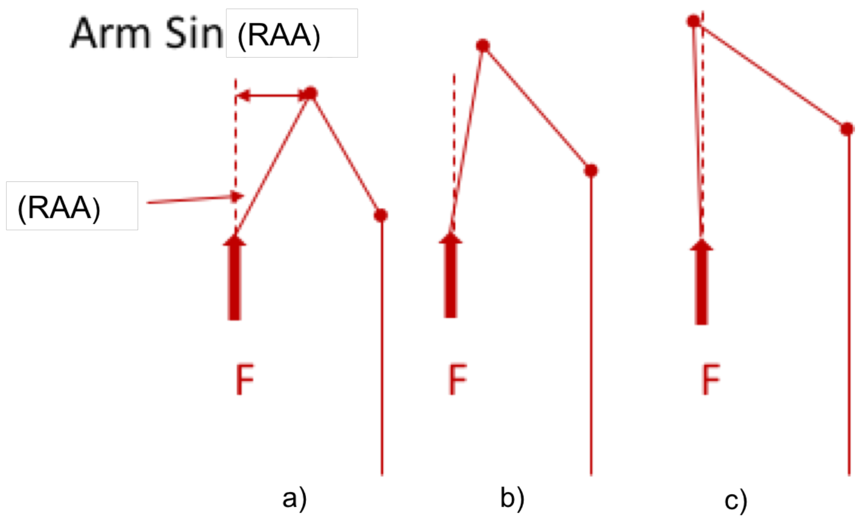
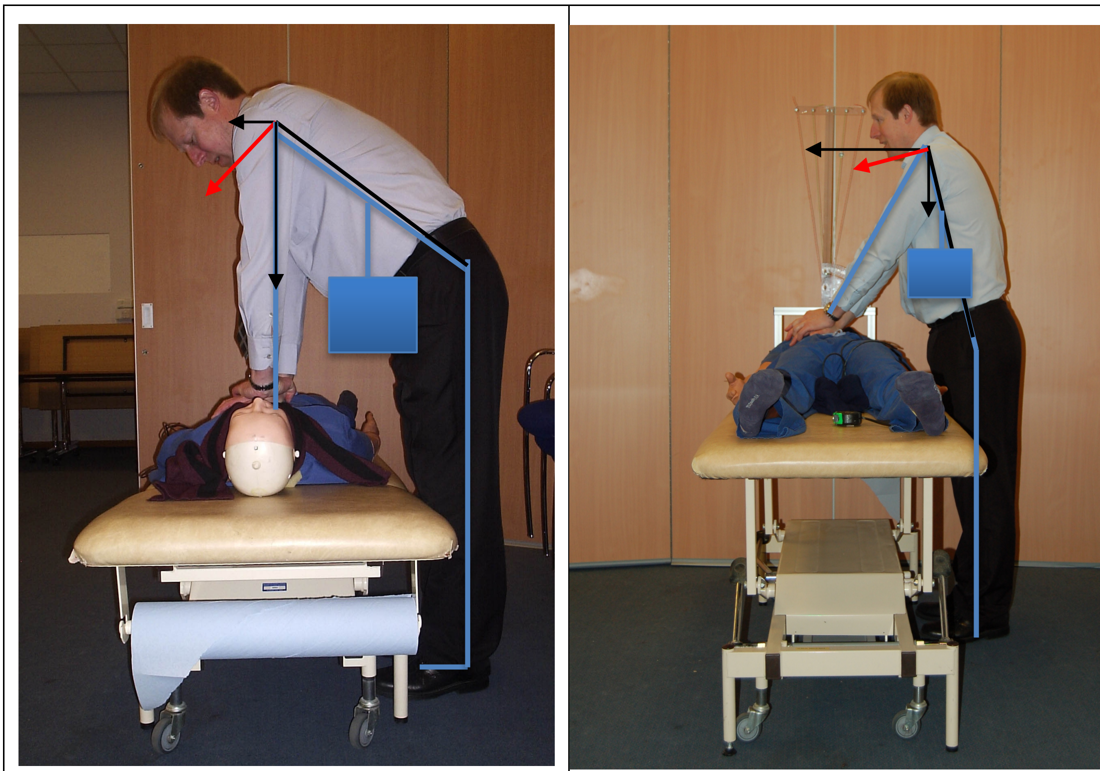


Figure 4-5 Biomechanical concept of arm moment for short (a), medium (b) and tall (c) rescuer at given platform height.

4.2.2 Torques



a. Rescuer posture at a low platform height

b. Rescuer posture at a high platform height

Figure 4-6 Image demonstrates altered rescuer posture and the proposed changes to rescuer forces derived from moments. The arrows represent the perpendicular moment (red arrow), vertical and horizontal forces (black arrows). The blue square represents the vertical force derived from rescuer body mass and gravity. A. demonstrates a low platform height with an increased upper body moment. B. demonstrates a high platform height and a reduced upper body moment.

4.2.3 Predicted vertical moments

Using Arm moment = FP. Sin(RAA) Equation 20 and $F_{VERT} = mg.Sin^2(RAB)$ Equation 19 the forces generated by the upper body and the moment at the shoulder may be calculated for a variety of platform heights and for a short, medium and tall rescuer (Figure 4-7). In calculating the moment about the shoulder it has been assumed that the depth of compression and therefore force at the patient's chest is constant. In reality this may not be achievable.

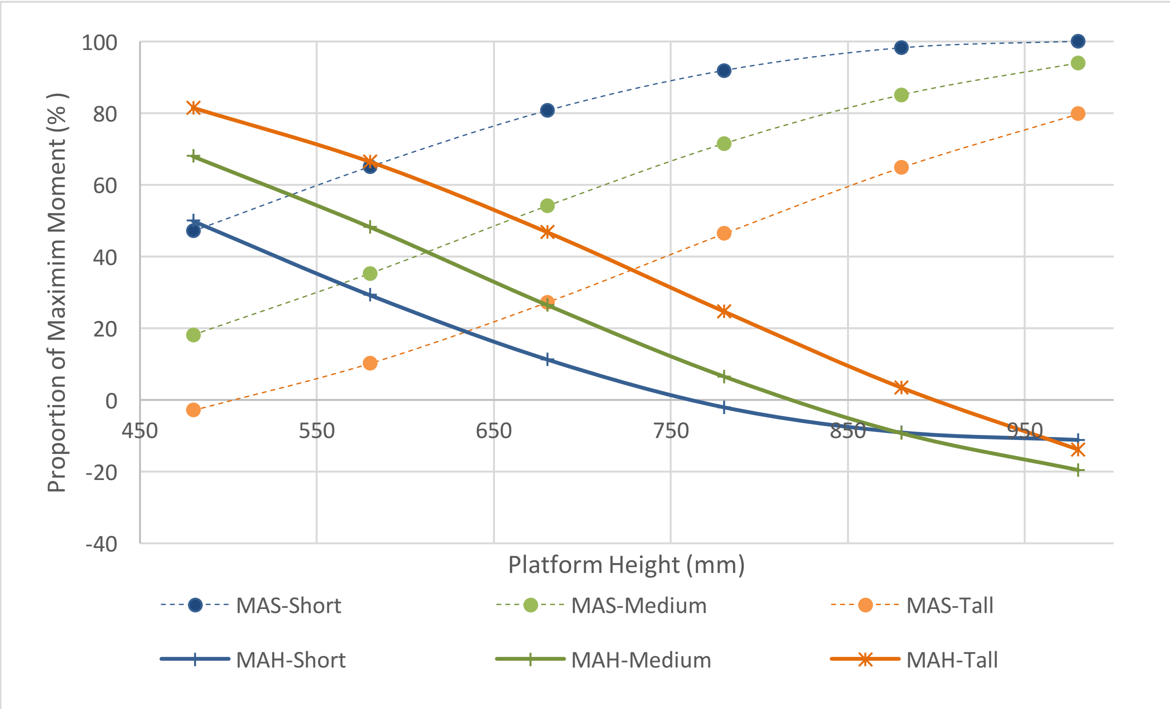


Figure 4-7 Predicted rescuer moments about shoulder (MAS) and moment about hip (MAH) for three different rescuer heights (short, medium and tall) across a range of clinically relevant platform heights.

The force generated by the upper body weight is maximal when the back is horizontal. Similarly, the moment about the shoulder is maximal when the arms are horizontal. Figure 4.7 demonstrates how these parameters vary as a proportion of these maximum values.

Ideally the force at the shoulders should be maximised whilst the moment about the shoulder should be minimised. Attention to the figure 4.7 demonstrates that low platform heights and tall rescuers offer an advantage. With the back close to horizontal the force due to rescuer upper body mass is divided equally between the rescuer arms and legs and therefore the force onto the patient is maximal. With the back almost horizontal the arms are close to vertical and hence there is no moment about the shoulders.

However, as the rescuer back becomes more upright it would be expected that the force due to muscles and motion decreases until it becomes zero when the back is vertical. Similarly, the moment about the shoulders increases as the back becomes more vertical indicating that shoulder muscles need to work harder to oppose the rotation.

Investigating the effects of gravity, muscular contractions and interfaces with respect to the depth of compression could identify the origins, contribution and limitations of rescuer forces. The posture of a rescuer, determined by the findings of chapters 3, could indicate the proportion of body mass a rescuer could potentially lean, passively using gravity, against a victim's chest. The magnitude of the leaning force may influence the depth of compression achieved, chest compliance dependent.

Furthermore, rescuer posture, for the same anatomical reasons, could determine which rescuer muscle groups are active and the magnitude of muscular activity during a pushing, active, action. Muscle groups could be active but ineffective due to their orientation to the task and also undergo accelerated fatigue. Those muscle groups would also be responsible for movement, accelerating and decelerating the upper body during chest compressions.

A comparison of leaning, pushing and dynamic chest compressions data could determine the origins, contribution and limitations of rescuer forces. Furthermore, altered posture could demonstrate the consequential changes to those forces.

4.3 Method

Ethical approval was necessary and granted by the Faculty of Medicine Ethics Committee (Appendix F) on 24th January 2012 (Ref RGO 901).
Recruitment posters were placed around an acute NHS Trust. Potential volunteers contacted the author for further details of the experiment. Each participant received a participant information sheet (appendix B) and completed a consent form (appendix C). Volunteers were excluded if they had not completed a BLS course approved by the Resuscitation Council (UK) within 12 months or if volunteers reported musculo-skeletal injuries. All participants were healthcare professionals working in an acute NHS trust. The recruitment process followed the same process set out in chapter 3 (section 3.3) of this thesis.

4.3.1 Procedure

Rescuers were instructed to adopt a posture to perform chest compressions for a range of randomised, clinically relevant, platform heights (48, 58, 68, 78, 88 and 98 cm). Platform heights refer to the superior surface of a non-compliant platform. Rescuers were blinded to the height of the platform and were not provided feedback on the quality of their performance during the delivery of chest compressions. All rescuers were rested prior to and between resuscitation activities.

1. Rescuers were required, using their arms, to passively lean their body weight against the resuscitation manikin (chapter 2) at each platform height. Depth of compression was recorded from the instrumented manikin. Rescuer posture was recorded by the CODA (chapter 2)system and the vertical force through the rescuer's feet was recorded from a ground force plate (chapter 2). The difference between the initial standing force plate weight and the residual weight was recorded as the leaning (passive) force.

2. From the leaning posture, rescuers were instructed to maximally push against the resuscitation manikin. Depth of compression was recorded from the instrumented manikin. Rescuer posture was recorded by the CODA[126,128,129] system and body weight was recorded from the ground force plate. The difference between the leaning weight and the maximum pushing weight was recorded as the active pushing component.

3. Rescuers were instructed to deliver chest compressions in accordance with the Resuscitation guidelines 2010[20], 30 chest compressions at a rate of 100-120 bpm and 2 rescue breaths. Rescue breaths were counted but not delivered to replicate BLS.

A metronome, set at a rate equivalent to 100 beats per minute (BPM), was used to aid rescuers in delivering chest compressions at the appropriate rate[18,36,58].

4.3.2 Data Sampling

Followed the same process set out in chapter 3.

4.3.3 Data Analysis

Followed the same process set out in chapter 3.

4.3.4 Force Plate Data Processing

Force plate data were processed in Matlab R2014a and exported into Excel (2007). Analysis of data was performed by SPSS (IBM) Version 22. All results are presented as a mean +/- standard deviation (SD). All data were graphically checked for normal distribution before applying appropriate statistical analysis.

4.4 Results

Twenty-one BLS trained volunteers (13 female (62%) and 8 male (38%) mean age of 37.9 years (SD 12.6) years participated in the study. The mean height of the rescuers was 1.70 m (SD 0.10) and mean weight 72.2 Kg (SD 16.3) (Table 13).

Table 13 Demographic data of the rescue population.

	Mean	SD	Range
Age (years)	37.9	12.6	18 - 50
Height (metres)	1.70	0.10	1.57 – 1.87
Weight (Kg)	72.2	16.3	40.6 – 120.6
BMI Kg/m^2)	24.8	5.03	16.5 – 35.2

4.4.1 Origin of Forces – Rescuer Weight

A t-test revealed a statistically significant difference between the leaning and pushing components for rescuer force (P=0.01). The mean leaning force was 217.0 N (SD 82.2) (95% CI 178.6 – 255.5 N) and pushing presented a mean of 150.2 (SD 53.7) (95% CI 125 – 175.3 N).

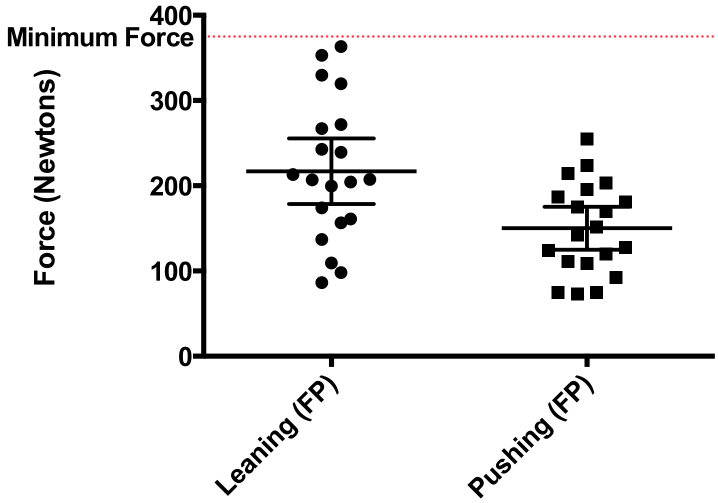


Figure 4-8 A scatter plot demonstrating the mean force (+/-SD) applied to the manikin for leaning and pushing. The minimum force (375 N) required to achieve 50 mm depth of compression is presented as a red dotted line. n21.

Effects of Rescuer Body Weight

Heavier rescuers could a lean a greater mass than lighter rescuers with 26.2% of force associated with rescuer mass. However, rescuers were not able to lean the minimum amount of mass to reach the required force (375 N) to achieve the minimum depth of compression (50 mm).

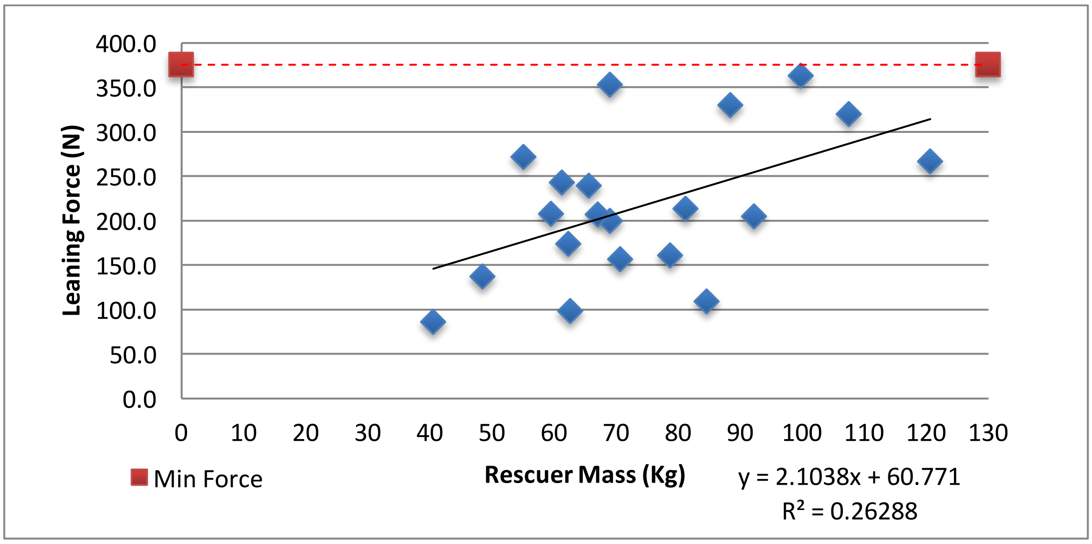


Figure 4-9 A scatter plot demonstrating the relationship between rescuer mass and the leaning force. n21. The minimum force required (375 N) to achieve a 50 mm depth of compression is presented as a red dotted line.

Forces Concept - Rescuer Upper Body Weight (optimum posture)

This experiment demonstrated a statistical significance (P=0.01) between rescuers leaning and pushing upper body weight against the resuscitation manikin. Matched rescuers were able to lean an average of 57.6% (SD 10.3) of their upper body weight and were able to push a mean of 41.1% (SD 7.9) of their upper body weight against the instrumented manikin.

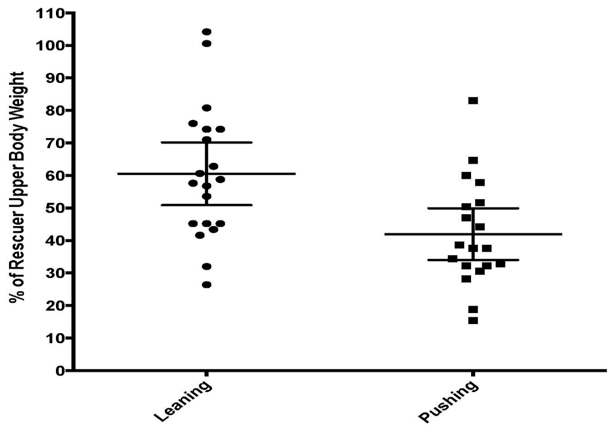


Figure 4-10 A scatter plot demonstrating the mean percentage of rescuer upper body weight (CI 95%) during leaning and pushing. n21.

Forces Concept (Leaning and Pushing) – Optimum Rescuer Posture

A t-test demonstrated a statistically significant difference between the mean depth of compression during leaning and pushing (P=0.001). Rescuers were able to lean their body weight to a mean depth of 25.7 mm (SD 7.3). This value accounted for 51% of the minimum depth of compression. In addition, matched rescuers were able to push their body weight to a mean depth of 17.2 mm (SD 7.6), representing 34 % of the target depth of compression.

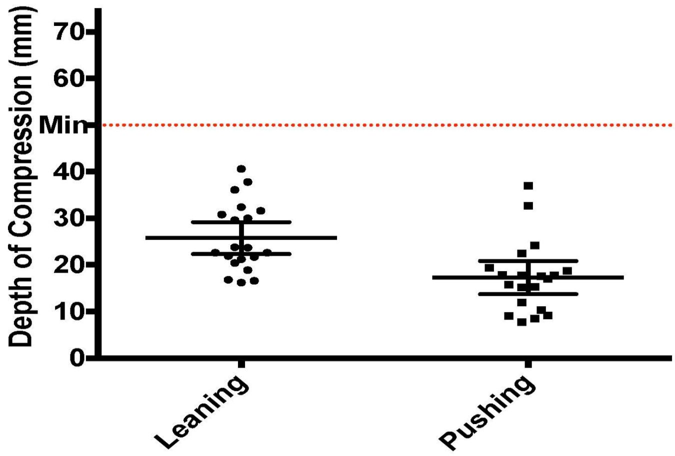


Figure 4-11 A dot plot demonstrating depth of compression from leaning and pushing (95% CI). The plot highlights (dotted line) the minimum depth of compression (n=21).

Forces Concept (LeanPush and Dynamic Chest Compressions) optimum posture

The two mean depths of compression were compared with a t – test, demonstrating no significant difference (P=0.9) between the data sets at the optimum rescuer posture. The combined leaning and pushing force (leanpush) demonstrated a mean depth of compression of 43.0 mm (SD 11.0) (95% CI 37.8 – 48.2) (Figure 4-12). Dynamic chest compressions (BLS) demonstrated a mean depth of compression of 43.0 mm (SD 7.9) (95% CI 39.4 – 46.6 mm).

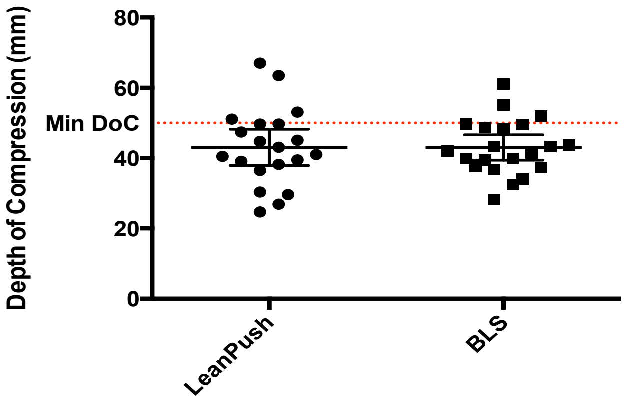


Figure 4-12 A dot plot demonstrating depth of compression from combined leaning and pushing (leanpush) and dynamic chest compressions (BLS) (95% CI) The minimum depth of compression is presented (red dotted line). n21.

Regression

Regression analysis revealed platform height to be most significant factor in relation to the depth of compression in leaning and pushing. Rescuer height and weight are also highly significant. Regression also revealed gender difference for these outcomes.

Table 14 Regression analysis of rescue parameters.

DOC (mm)	Estimate	CI (95%)	P Value
Platform Height	0.41	0.17 to 0.65	0.000
Rescuer height	-0.35	-0.43 to -0.28	0.001
Leaning (N)			
Platform Height	-2.38	-2.90 to -1.85	0.000
Rescuer Weight	2.06	1.36 to 2.77	0.000
Pushing (N)			
Platform Height	-1.32	-1.76 to -0.88	0.000

Forces Concept (Optimal versus Sub-optimal Rescuer Posture) – Depth of Compression

Chapter 3 established deviation from the optimum rescuer posture degraded BLS performance. In addition, the angle of the rescuer's shoulders (RAA) and back (RAB) were inversely related. Figure 4-13 demonstrates the relationship between the mean rescuer back angle (RAB) and the contribution of the leaning, pushing and dynamic forces used to compress the manikin's chest. At the lowest platform height (48 cm) with a mean RAB of 46° (SD 4.5), the depth of compression achieved is derived from the leaning and pushing components. As RAB decreased i.e. rescuer back became more vertical, depth of compression cannot be exclusively attributed to the leaning and pushing components. A third component, i.e. the difference from the combined leanpush component, and the depth of compression achieved during dynamic chest compressions is evident.

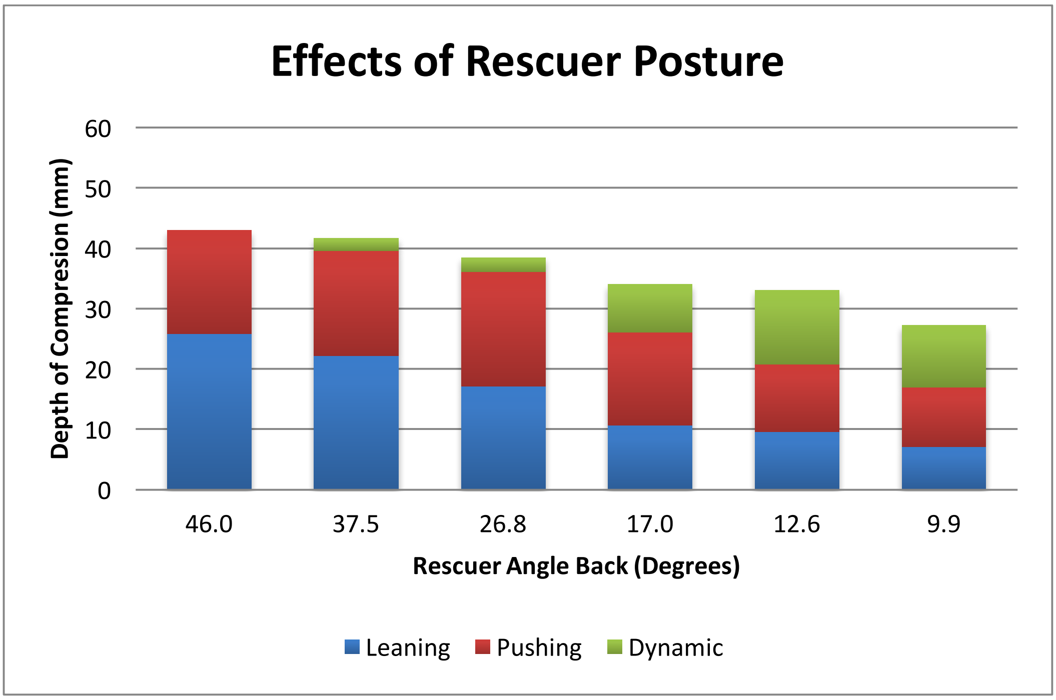


Figure 4-13 A stacked bar chart demonstrating the effects of rescuer posture on the contribution of leaning, pushing and motion for decreasing back angles (RAB). n21.

Rescuer back angle decreased from 46° (SD 4.5) to 9.9° (SD 5.7), the third, dynamic, contribution increased from 5% to 36%. Notably at a back angle of 26.8° to 17.0° the contribution from leaning and pushing differs. Pushing marginally became the larger contributor towards the depth of compression. With decreasing angles, the dynamic component became the greater contributor of chest compressions.

Forces concept (Optimal versus Sub-optimal Rescuer Posture) – rescuer upper body weight

The data demonstrated the effect of rescuer posture on the contribution of rescuer upper body weight. Rescuers in the optimum posture achieved an average of 56.5% (SD 10.3) of their upper body weight whilst leaning on the manikin. The leaning contribution diminished to 26.0% (SD 5.0) as rescuer back angle (RAB) became vertical, representing a 50 % reduction in rescuer upper body weight being applied to the manikin.

In addition, at the highest back angle (46°), rescuers could push an average of 41.1% (SD 7.9) of their upper body weight. This is also reduced almost by half to 23.6% (SD 6.0) at a more vertical posture (9.9°). This suggests rescuer posture is determining the magnitude of muscular activity.

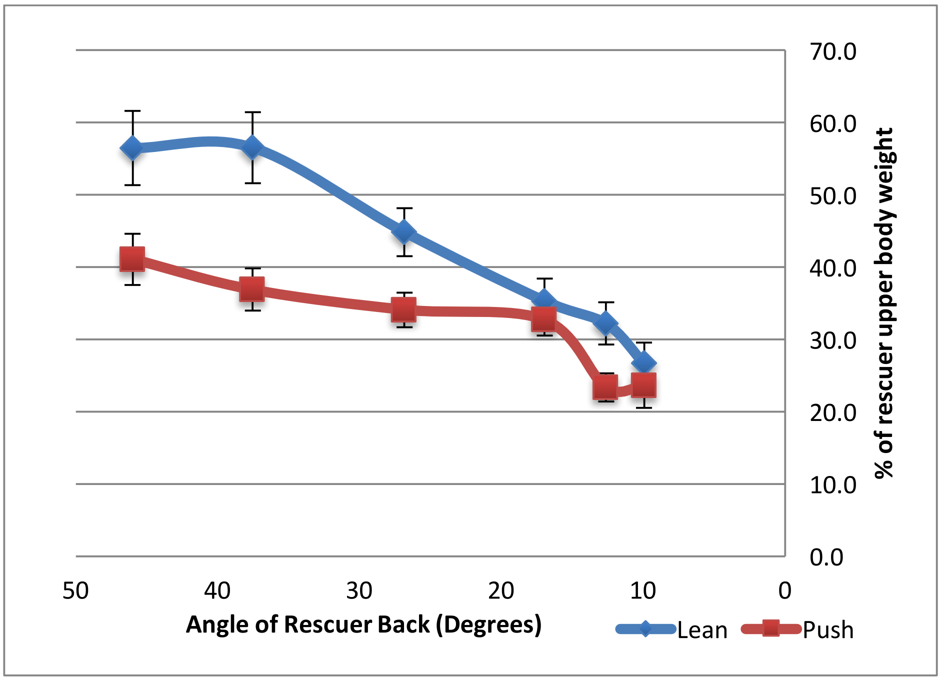


Figure 4-14 A line graph representing the association between Rescuer Angle (RAB) and the % of rescuer upper body weight during leaning and pushing (+/- SEM).

4.4.2 Quality of Rescue Attempts – Optimum Rescuer Posture

The percentage of rescuers able to achieve the target (2010) depth of compression in the optimum rescuer posture was poor (figure 4-15). Out of 21 rescuers, 4 (15%) rescuers were able to meet the resuscitation guidelines depth of compression (50 mm)[58].

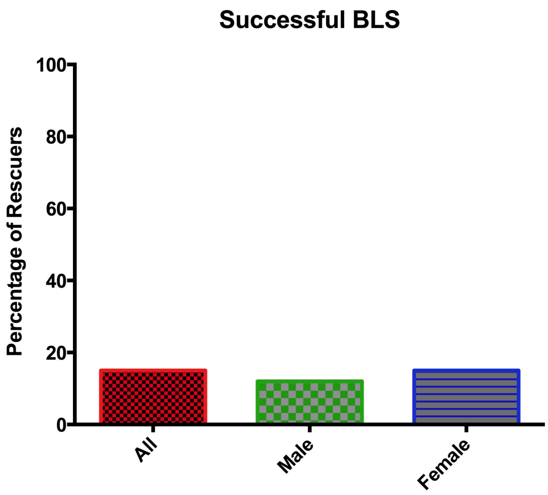


Figure 4-15 A bar chart demonstrating the percentage of successful rescue attempts for the cohort and by gender.n21.

Depth of Chest Compressions – Optimum Rescuer Posture

The minimum depth of compression recommended by the Resuscitation Council (UK) is 50 mm. Data derived from 2 cycles of 30 chest compressions demonstrated the mean depth of compression achieved for the rescue population was 43.6 mm (SD 7.7) and a median of 42.1 mm. The difference between the mean depth of compression and the minimum depth of compression was 7 mm.

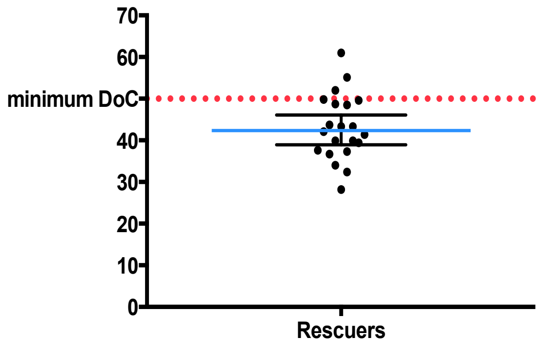


Figure 4-16 A dot plot demonstrating the mean depth of compression for the rescue population (95% CI). The plot also highlights the minimum depth of compression. n21.

4.5 Discussion

This section will outline the key finding of chapter 4 and discuss the details of the forces concept. Further work and limitations will be discussed in chapter 5.

This is the first study to present a forces concept for simulated in-hospital resuscitation applied to a range of clinically relevant platform heights. The concept proposed to identify the ergonomic forces used to compress a manikin's chest, and determine the effects of sub-optimal posture on those forces. The foundation of the forces concept was the geometrical relationship (chapter 3) between the rescuer and the manikin using moments. Rescuer posture is determining the effectiveness of the upper body mass and muscles to compress the chest. Therefore, the angle of the rescuers upper body (RAA and RAB) determines the depth of chest compressions achieved by BLS trained rescuers.

The majority of the force used to compress a chest, in the recommended posture[20,58], can be attributed to the leaning component of rescuer upper body weight. The pushing component of rescuer upper body weight contributed a smaller force. In the optimum rescuer posture, leaning accounted for 56.6% and pushing 41.1% of the rescuer's upper body weight against the manikin. The combined output of leaning/pushing activity equalled that achieved during dynamic chest compressions.

This suggests, in the optimum rescuer posture, the maximum contribution of the rescuer's upper body when leaning has been reached due to physical constraints or additional contribution from the rescuer's upper body weight is being distributed ineffectively.

Sub-optimal posture reduces leaning and pushing rescuer forces. At a maximum RAA and minimum RAA both leaning and pushing were reduced by 50%

These finding supports the forces concept of the upper body moment at the hip. The rescuer's back angle (RAB) is at a maximum value, increasing the perpendicular distance and utilising the upper body mass to deliver a vertical force. As RAB decreases, the upper body moment decreases demonstrating a reduced upper body contribution. This indicates the forces used to compress a patients' chest are directly attributed to the rescuers physical upper body attributes but influenced by posture.

In the optimum rescuer posture, pushing contributed a smaller force than leaning but diminished by a similar amount for sub-optimal posture. However, it is unclear as to the ratio of mass and muscles within the rescuer's upper body. Pushing is an active event created by the contraction of muscle groups. Muscle groups are numerous and complex within the upper and partially lower body[137]. In the optimum posture, rescuer arms were in a vertical plane and acted as a conduit for the forces generated by the upper body during the pushing activity. As rescuer posture altered, the arms changed to a horizontal plane. Increasing the arm moment about the shoulder but decreasing the efficiency of the muscular activity. Smaller shoulder muscles would become engaged to move the upper and lowers arms in a vertical plane and prevent rotation caused by the resistance of the manikin's compliance.

An additional component has been identified and initially termed a dynamic component. Sub-optimal rescuer posture marginally increased the dynamic contribution of forces used to compress the manikin's chest.

The contribution of the rescuers upper body weight is maximal (97.7%) in the optimal rescuer posture. The leaning component delivered by the rescuer's upper body weight achieved 50% of the required depth of compression (50 mm). The pushing component accounted for 34% of the required depth of compression. However, the combination of leaning and pushing failed to repeatedly achieve the required depth of compression 50 mm (85%). The mean depth of compression achieved by qualified BLS rescuers is below the published minimum depth of compression[18,20,98]. This study agrees with similar findings to chapter 3 of this thesis.

4.5.1 Conclusion

The depth and quality of chest compression in a simulated in-hospital cardiac arrest is poor. The forces concept revealed the force used to compress a manikin's chest is predominately derived from the moment of the rescuer's upper body mass pivoted at the hips and is assisted by muscle groups. The contribution of the upper body is greatest in the rescuers optimal posture, exploiting the moment created by the upper body. A third dynamic component has no effect on the depth of compression in the rescuers optimum posture.

In a sub-optimal rescuer posture, the overall quality of chest compressions is degraded further. As rescuer back angle increased the moment at the shoulders is greater than the moment at the hips. Therefore, the contribution of upper body mass and muscles is attenuated. However, the dynamic contribution increased. Without recognition these of these findings, sub-optimal chest compressions could contribute towards ineffective BLS with a potential detrimental physiological consequence.

The translation and application of the findings from chapter 4 and chapter 3 are presented in chapter 5.

5 Discussion

This research set out to determine the effect of platform height on the depth of compression achieved during a simulated in-hospital cardiac arrest. It also determined the underlying mechanisms affecting the depth of compression associated with rescuer posture. The thesis identified rescuer, patient and medical platform as key factors (Figure 5-1) impacting on the depth of compression. During a cardiac arrest the resistance presented by the patient's chest must be overcome by the rescuer utilising their physical attributes. Rescuer height is an unknown and variable factor. For an in-hospital cardiac arrest, the modifiable clinical environment is the height of the medical platform height.

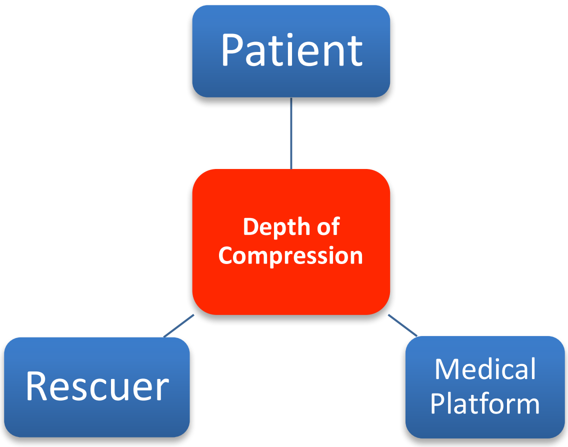


Figure 5-2 - Factors affecting depth of compression

It was proposed that platform height and rescuer height determine rescuer posture, which when combined with rescuer weight/muscles defines rescuer force. The magnitude of the force applied to the rescuer's chest determines the depth of compression and therefore the quality of lifesaving treatment (Figure 5-2).

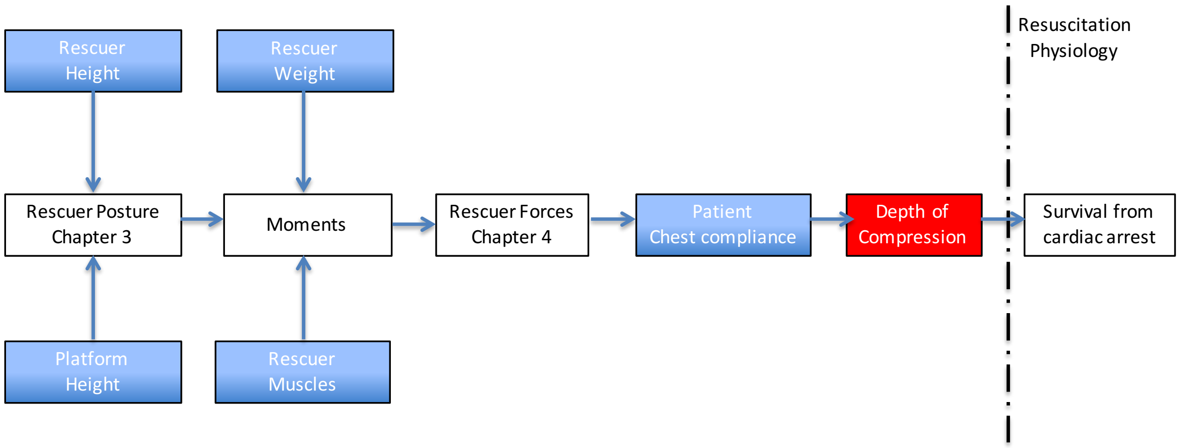


Figure 5-2 Overall concept of the thesis.

This study is unique in that it is the first to use a clinically relevant range of platform heights (48-98 cm) to demonstrate the effects of platform height on depth of chest compressions during a simulated in-hospital cardiac arrest. The maximum depth of compression was achieved at lowest platform height.

This study also examined the origins of rescuer forces are derived from the body weight and muscles of the rescuer. Rescuers leaning upper body mass accounted for the majority of the force used to compress the chest with rescuer pushing accounting for the additional force.

Therefore, failure to correctly position a patient on a medical platform at an appropriate could reduce the efficacy of resuscitation efforts and compromise the patient's chance of survival following a cardiac arrest.

This chapter explores the evidence presented in this thesis and its application to clinical practice.

5.1 Depth of Compression

The methodology employed for this work addressed the clinical aspect not considered from previous studies by using a range of clinically relevant platform heights. Existing studies[81,83,84,88-91,138,139] have not incorporated the heights specified by British Standards for medical platforms, nor the heights pre-programmed into the CPR facilities on medical beds, and presented conflicting results. These investigations have provided clarity by demonstrating the detrimental effect of elevated platform heights on the depth of chest compressions during a simulated in hospital cardiac arrest.

Two independent experiments presented in this thesis provide evidence that medical platforms should not be positioned above 68 cm for resuscitative treatment and suggest current CPR facilities may be programmed too high for the delivery of optimal BLS. Data from the experiments demonstrated a statistically significant reduction in the depth of compression at a platform height of 68 cm and above compared to that achieved at 48 cm ($P<0.01$). 68 cm is lower than the CPR height setting on the medical platforms evaluated for this thesis (Table 2). Currently medical platforms with a CPR facility, once activated, will position a patient at a height of 72 or 75 cm, model dependent. A difference of 4 to 7 cm in height could affect the depth of compression achieved during BLS.

Rescuer height and weight are uncontrollable variables during a cardiac arrest. Rescuer height became statistically significant at platform heights >78 cm. At 48-68 cm there was not a statistically significant correlation between rescuer height and depth of compression. This supports the previous claim that platforms should not be positioned above 68 cm. This would minimise the impact of rescuers with a shorter stature and limit the delivery of sub-optimal BLS.

Rescuer weight is a major contributor to the depth of compression. Leaning accounted for 51% of the required depth of compression for the 2015 guidelines. Lighter rescuers achieved a lower depth of compression than heavier rescuers when leaning against the manikin (Figure 4-9).

5.1.1 Rescuer Posture

In these two experiments, rescuers did not acquire the correct posture for the delivery of BLS. Resuscitation guidelines[18,36,55] advocate shoulders are positioned vertically over wrists (Figure 1-4), however none of the rescuers achieved this posture at any platform height. Therefore, the recommended rescuer posture is not being attained for the current range of platform heights i.e. beds, recommended by British Standards.

Platform height determined rescuer posture. As platform height increased; rescuers arms became more horizontal and backs more vertical. At a platform height of 48 cm the average shoulder angle (RAA) was 15.0° (SD 6.6) and the average back angle (RAB) was 49.4° (SD 4.8) and associated with a mean depth of compression of 43.0 mm (SD 9.5). Increasing platform height deviated further from recommended rescuer posture with subsequent attenuation in depth of compression. At the tallest platform height (98 cm) the mean RAA was 61.3° (SD 8.8) and RAB 3.5° (SD 2.7) with a mean depth of compression of 27.3 mm (SD 6.4) resulting in an almost vertical rescuer posture.

Shorter rescuers are more vulnerable to sub-optimal posture and less likely to achieve the recommended posture. Rescuer height and rescuer shoulder angle become significant at 68 cm and above. Shorter rescuers demonstrating a greater shoulder angle than taller rescuers. Therefore, taller rescuers achieved a lower RAA over a greater range of platform heights. The change in posture is associated with lower quality BLS.

To optimise resuscitation guidelines for rescuer posture, minimise the effects of rescuer height and maximise depth of compression, medical platforms should be positioned at 48 cm. A platform at 48 cm is within the British Standards range for medical platforms and should be considered for the standard height for the CPR facility. However other variables are considered in further work.

5.1.2 Rescuer Forces

Origins of rescuer forces and rescuer posture and how they contribute to depth of compression were identified in chapter 4. It proposed rescuers are equipped with mass, muscles and motion to compress a patient's chest. At the lowest platform height (48 cm) rescuer forces (lean and push) achieved a mean 85% of the guideline depth of compression. Increasing platform height, altered rescuer posture and attenuated rescuer forces by a maximum of 50% for both leaning and pushing. Rescuer forces are derived from the passive application of upper body mass, active contraction of upper body muscles and momentum.

Leaning

Leaning contributes the greatest amount of force. At the lowest platform height (48 cm), optimal posture, rescuer's leaning achieved a mean of 51% (25.7 mm SD 7.3) of the recommended depth of compression. This depth of compression equates to an average of 57.6% of the rescuer's upper body weight being leaned onto the manikin.

The moment generated by gravity on the rescuer's upper body decreases as rescuer posture (RAA & RAB) changes due to increasing platform height. The rescuer upper body moment is a product of force and perpendicular distance. Whilst for an individual rescuer the force is constant i.e. upper body mass, the perpendicular distance decreases as rescuer posture becomes more vertical and therefore less force can be applied to the manikin during leaning action which manifested as reduced depth of compression.

Heavier rescuers are able to lean more force onto the patient than lighter rescuers with a consequent greater depth of compression. However, all rescuer leaning forces would or could be vulnerable to an inappropriate platform height. Lighter rescuers would need additional forces i.e. muscles and motion, to address the deficit in depth of compression.

Female rescuers are at a greater risk of delivering sub-optimal chest compressions due to lower body weight. Female rescuers were lighter than male rescuers (Table 6 and Table 13) in this experiment and achieved a lower depth of compression than male counterparts at all platform heights across both investigations. Regression analysis (chapter 4) identified female rescuers achieved 33.2 N less force than male counterparts

Pushing

At the lowest platform height (48 cm), optimal posture, rescuer's pushed an average 34% (17.2 mm SD 7.3) of the recommended depth of compression which corresponds to 41.1% (SD 8.2) of rescuer upper body weight. In this posture the rescuer's upper body moment, described previously, is at its maximum and additional complex trunk muscles contributed during the pushing phase. Rescuer's arms are in a vertical position and muscular effort is transferred from the upper body to the manikin via the rescuer's shoulders along the arms to the rescuer's hands maximising the vertical force component.

The change in rescuer pushing forces is attributed to the change in rescuer moments at the hips and shoulder. As platform height increased, rescuer back angle (RAB) decreased and the shoulder angle (RAA) increased. The rescuers' upper body became more vertical and rescuer arms became more horizontal. The change in RAA increased the shoulder moment but attenuated the upper body moment and reduced the vertical pushing force. The pushing component from the arms relied upon rescuers arm and shoulder muscles to compress the chest. These muscle groups are smaller than trunk muscles and could be working ineffectively due to the angle of application. Muscle orientation and configuration of shoulders and trunk would need to be considered for future work.

Motion

There was no statistically significant difference between the combined Leanpush action and the dynamic CPR (100-120 bpm) in the optimum rescuer posture (P=0.9). The effects of repeated compression and decompression at 100-120 bpm became evident at the higher platform heights (figure 4.10). Further work would need to consider momentum as a factor of rescuer forces.

Rescuer forces summary

In summary, leaning accounted for greater depth of compression than pushing, rescuers need a minimum of 37.5 Kg upper body mass to lean the required force to compress an adult chest 50 mm. Changes in rescuer posture, caused by inappropriate platform height will attenuate both the leaning and pushing component by up to 50% and degrade the quality of resuscitation treatment. Rescuer motion only became evident at taller platform heights.

5.2 Quality of BLS

The number of rescuers achieving the required depth of compression was poor in both experiments (chapter 3&4). Rescuers achieving the required depth of compression was greatest at the lowest platform height (48 cm) in both experiments 63% (chapter 3) and 23% (chapter 4). Notably, rescuers from chapter 4 were required to compress to a greater depth than chapter 3 due to the change in resuscitation guidelines in 2010 during these experiments. Both studies demonstrated as platform height increased, the number of rescuers achieving resuscitation compression criteria reduced. At the tallest height (98 cm) 5% of rescuers achieved published compression depths (chapter 3) and 4% (chapter 4). Despite demonstrating statistical significance at 68 cm for depth of compression, clinically it would be more important to maximise the number of rescuers achieving the minimum depth of compression.

5.2.1 Gender

The experiments of this thesis has identified rescuer gender is an important factor in the quality of BLS, as gender is related to rescuer height. Based upon current resuscitation guidelines[58] between 50 to 60% of female rescuers failed to obtain the correct depth, across all platform heights compared with 30 - 40% for males. In the second investigation (chapter 4) no female rescuers achieved the minimum depth of compression at a platform height of 78 cm and above, despite 78 cm being slightly above the CPR height setting (Table 2) and within British Standards for medical platform height. The large proportion of female health professionals suggests more work is needed to explore the impact of gender on the quality of chest compressions in a hospital environment.

5.2.2 Resuscitation Guidelines

In the series of investigations for this thesis, at the lowest platform height (48 cm) 63% of rescuers performed chest compressions in accordance with the 2005 resuscitation guidelines[19] (40-50 mm)(chapter 3), and 23% of rescuers achieved chest compressions to the 2010 guidelines (50-60 mm) (chapter 4).

The change to the minimum depth of chest compression in 2010[18] was not accompanied with recommendations for rescuers to improve their existing poor performance. Therefore, it is unclear how rescuers unable to achieve a lower depth of compression (40 mm) would obtain an increased depth (50 mm) without scientific evidence to change practice. Furthermore, the percentage of rescuers achieving the minimum depth of compression reduced further with increasing platform heights in both experiments. Platform heights that are within the accepted range for British Standards.

However, ILCOR did recognise the limitations and weak scientific evidence for the change in resuscitation guidelines[56]. Since 2010, ILCOR have improved their processes for reviewing resuscitation science and introduced a methodological approach i.e. Grading of Recommendations, Assessment, Development and Evaluation (GRADE) and task forces to investigate specific areas of resuscitation, including BLS and education. Although the 2015 guidelines for depth of compression are primarily based on out of hospital studies[21], suggesting further work is required for in hospital cardiac arrests.

5.3 Potential Limitations

This research set out to determine the effects of platform height on the depth of chest compressions in a simulated clinical environment. The results demonstrated a statistically significant reduction in depth of compression between a platform height of 48 and 68 cm in two separate investigations. However, the experiments employed 10 cm intervals in platform height to encompass the range of heights determined by British Standards. Smaller increments between platform heights would provide greater precision on the exact height of statistical significance.

The height range used for the study included the range of platform heights encountered clinically i.e. hospital beds, but did not encompass platform heights lower than 48 cm. The lowest height setting (48 cm) demonstrated not all rescuers complied with resuscitation guideline rescuer posture. Investigating lower platform heights would provide a clearer insight into postural changes and rescuer forces across all medical platforms used within the NHS, including stretchers, theatre trollies and examination couches.

5.3.1 Study Size and Demographics

The size of the study population was powered to detect a significant change in depth of compression with a study size similar to previous studies[83,84,88,91]. However, to consider variations in rescuer attributes a future study should include the full range of rescuer height and weights likely to be encountered as part of a resuscitation team.
It was not clear from the study population the occupational status of each volunteer. However, all volunteers were BLS trained within 12 months, as per resuscitation guidelines, and worked as healthcare professionals within an acute NHS trust. Therefore, volunteers would be expected to perform BLS as a healthcare professional or as part of the cardiac arrest team. It was also unclear from the study population of those volunteers who had previous experience delivering BLS during a cardiac arrest. Although both experiments demonstrated a marginal difference between gender. This may not reflect the ratio of male and female healthcare professionals working in the NHS.

5.3.2 Rescuer Posture

Observation of rescuer posture using CODA data revealed rescuers deviated from the intended protocol during BLS. Lower platform heights revealed shorter rescuers slightly leaning into the platform whilst in contrast taller rescuers were observed displaying posterior hip movement. The protocol required a fixed distance between the rescuer and manikin. In addition, rescuer elbow flexion was observed at increasing platform heights and affected shorter rescuer at lower heights. These additional rescuer movements would impact on the geometrical model to predict rescuer posture for a range of clinically relevant platform heights.

5.3.3 The Model

The geometrical model set out to predict rescuer posture, inclusive of rescuer height across a range of clinically relevant platform heights and demonstrated similar RAA and RAB. However, anatomically the human adult body is not a 2D linear structure. Bodily structures are linked together with joints allowing flexion and extension between segments. A rescuer's spine is not linear and the functional anatomical curvature of the spine provides support and movement to the rescuer. The vertebrae of spine permit a degree of movement[140] depending on the type and location of the vertebrae, all of which could influence the rescuer's posture and therefore the accuracy of the model. The geometrical model considered the rescuer's arms to be linear structures that acted as a conduit between the rescuer and the manikin. Images derived from CODA revealed flexion at the elbow that would need to be considered for future model development.

5.3.4 Instrumented manikin

The instrumented manikin was developed and built because no commercial solution was available at the time of the experiments. The work required a resuscitation manikin with a chest compliance with a curvilinear chest compliance[77], similar to an adult human chest. The manikin was built with a compression spring with a linear compliance, however the compliance was similar to the median human chest compliance (Figure 1-7).

Despite developing a manikin with similar chest characteristics, limitations were evident. The difference in compliance characteristics presented in Figure 5-3 demonstrates rescuers applying more force on a curvilinear chest (blue line) will not necessarily produce a greater depth of compression. Therefore, rescuers with a greater upper body mass and muscles would not necessarily improve the quality of their BLS. In contrast, rescuers applying more force to a linear chest characteristic (red line) will achieve a greater depth of compression.

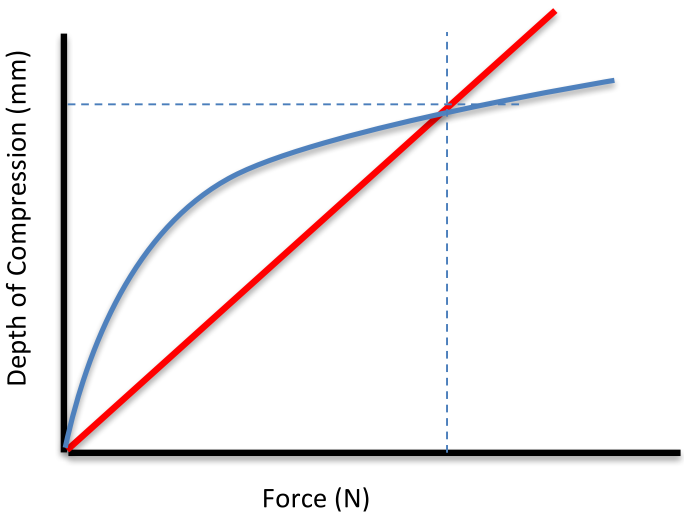


Figure 5-3 Line graph demonstrating the difference in a linear force-depth relationship of a compression spring (red line) and a curvilinear force depth relationship human chest (blue line).

5.3.5 Rescuer Back Pain

Ergonomics is used to prevent or limit injuries to the workforce[96,99,141]. Chest compressions require repetitive muscular activity and mechanical stress which can initiate or aggravate low back pain[142]. These experiments did not set out to investigate rescuer back pain, however, Tsou et al[143] examined platform height to determine rescuer posture and spinal loading. Tsou et al[143] reported taller platform heights are associated with lower spinal loading and greater spinal loading at lower platform heights. Lower platform heights demonstrated optimum resuscitation performance, as demonstrated in this thesis. In contrast, higher platforms are associated with sub-optimal chest compressions. This presents a potential dilemma between the survival of the patient and long-term occupational health of trained rescuers. The lower platform height supports the need to rotate rescuers every 2 minutes to limit back injuries but incurs a relative rescuer height problem previously raised.

The recruitment process for these experiments excluded participants who reported existing back pain or any skeletal problems. The experiments did not record any injuries caused by delivering chest compressions at different platform heights or followed up the rescuers to determine if they experienced back pain subsequent to the experiments.

5.3.6 Rescuer Fatigue

The delivery of continuous chest compressions to a patient requires a sustained, repetitive workload for the rescuer. This study requested rescuers to perform 2 cycles of 30 chest compressions, lasting approximately 40 seconds, but did not explicitly measure signs of rescuer fatigue. All rescuers were rested prior to and between each rescue attempt. The order rescuers performed chest compressions were randomised to exclude rescuer fatigue as a variable. Foo et al[144] investigated and reported rescuer posture (RAA and RAB) impacted on rescuer fatigue. However, the range of platform heights used by Foo et al[144] were not inclusive of a clinical range of platform heights, therefore has limited clinical impact and application and further work would be required.

5.4 Implications of thesis

The following section highlights those areas where the findings of this research could be applied to improve practice within the resuscitation environment, in and potentially out of hospital settings. The translational aspect of this thesis has been optimised with consideration of the criterion and required elements from the simulation literature[120].

5.4.1 CPR Platform Height Setting

The CPR height setting for the audited platforms (table 2) is determined by manufacturers of medical platforms. This potentially presents resuscitation providers with a sub-optimal environment and could comprise the implementation of the Chain of Survival (figure 1.1). The CPR height setting for the Arjohuntleigh platforms are higher than the statistically significant height (68 cm), identified in these investigations. Therefore, patients experiencing an in-hospital cardiac arrest on a medical bed would be positioned higher than the height demonstrating a statistical difference in depth of compression. Interpretation of data and the CPR setting for a typical medical platform (Table 2), indicates rescuers would be unable to acquire the recommended rescuer posture. Therefore, limiting the application of rescuer upper body attributes and deliver sub-optimal BLS. This presents an opportunity to improve the synergy between British Standards for medical platforms and current/future resuscitation guidelines.

5.4.2 Geometrical Model and Forces Concept

The novel geometrical model and forces concept presented in this thesis could contribute towards the development of an ergonomic approach towards BLS. Demographic rescuer data could be used to predict RAA and RAB for an accepted platform height and present the potential forces available to a rescuer using the FPJ. Alternatively, the FJP could identify the relative height the platform should be positioned to achieve recommended RAA and RAB. Lower platform heights optimise rescuer upper body attribute but increase risk of injury to the rescuer's lower back. However, either approach would have to consider the British Standards for medical platforms and the CPR function.

5.4.3 Ergonomics

Resuscitation guidelines advocate activating the CPR function, if available (chapter 1) or positioning the platform to the rescuer's mid-thigh height. These recommendations present contrasting ergonomic methodologies[96,99,145] 1. Fitting the Person to the Job (FPJ) using the CPR function and 2. Fitting the Job to the Person (FJP) using the mid-thigh height.

Fitting Person to the Job (FPJ) methodology would require selecting rescuers physically capable of achieving the minimum depth of compression for a universally accepted CPR platform height, currently suggesting taller heavier rescuers. Data from my investigations suggests the FPJ approach would exclude shorter, lighter rescuers, irrespective of gender, from participating as a member of the cardiac arrest team. Although if this was to become the preferred ergonomic methodology, the geometrical model and forces concept created from this thesis could be used, with development, to identify those rescuers with or without the appropriate attributes to achieve the required depth of compression. Therefore, a rescuer selection process would be necessary and include rescuer attributes, resuscitation education, safety and skills training.

The Fitting Job to the Person (FJP) methodology would require an adjustable platform height relative to each rescuer i.e. mid-thigh height. This platform height would optimise, but not necessarily achieve a recommended rescuer posture (RAA of 0°) for the individual rescuer but could maximise rescuer forces. However, the FJP approach could require repeated adjustment of platform height as members of the resuscitation team rotate, every 2 minutes, in accordance with resuscitation guidelines[18,36,58] to prevent rescuer fatigue. Adjustment of platform height could be time consuming, interrupt high quality chest compressions[30] and ultimately degrade resuscitation physiology.

5.4.4 BLS Education and Training

There is an expectation from the public that all healthcare personnel are adequately educated and trained to perform chest compressions[58]. Current BLS education and training practices are presenting BLS rescuers with conflicting methodologies. BLS training sessions are typically performed with the manikin on the floor[146,147] with the BLS rescuer kneeling adjacent to the manikin, as visually portrayed in resuscitation literature[20,36,58,148]. This posture permits the rescuer's shoulders (RAA) to be positioned in accordance with guidelines[18,36,55,58] allowing rescuers to develop psychomotor skills. However, the majority of in-hospital cardiac arrests (97%) occur with a patient on a medical platform i.e. hospital bed (section 1)at a height determined by manufacturers. Therefore BLS training performed on the floor could prevent or limit the psychomotor skills development i.e. initiation of the muscle memory (adaptation)[145]. Furthermore, sub-optimal posture could promote and accelerate de-skilling.

5.4.5 Rescuer Skills Retention

Previous BLS studies have indicated a reduction in skills performance from 2 weeks to 2 months[147,149-155]. Despite the overall poor quality of BLS for my experiments, all rescuers had been BLS trained within 12 months, in accordance with guidelines[18,36]. However, the rescuer dataset did not include the date of the rescuer's last certification of BLS. Potentially, the time period between BLS certification could be between 1 to 364 days. Time periods between BLS training episodes have been associated with poor skills retention[150,152,156,157].

However, from a clinical aspect, during an in-hospital cardiac arrest, the dates of re-certification for BLS skills for each rescuer would not and are not considered. Furthermore, the experience of each rescuer is not questioned during a cardiac arrest. Rescuer audit post resuscitation would be necessary to evaluate any impact skills retention.

However before a skill can be retained, it has to be learnt. The learning of a skill i.e. chest compressions, was identified by Kroemer et al[145] as two processes, namely learning a movement and adaptation. The learning of movement is the repeated movement of relevant body parts that are then learned by the brain. As the movement is learned, the learner's brain, transits from a conscious to a reduced conscious state. The automatic reflex movements replace the conscious effort and control of movement.

Secondly, adaption includes the development of specific muscle groups(psychomotor skills). Repeated training episodes at a specific platform height e.g. 48 cm or below, will adapt appropriate muscle groups to the task and create muscle memory. Muscle fibres will thicken and therefore increase strength over time[137]. Poor rescuer positioning caused by inappropriate platform height will recruit muscle groups not adapted or developed for the delivery of BLS. Those muscles would be ineffective for the task and therefore fatigue at a quicker rate than a muscle appropriately positioned for the task. Consequential degradation in the quality of BLS skills will ensue.

5.4.6 Modification to Resuscitation Practice

Rescuers unable to achieve a RAA of 0° whilst standing adjacent to the patient, [55] , are instructed to kneel on the medical platform. This presents risks to the rescuer, including; risk of injury from impending electrical defibrillation, bodily fluids and needles. Furthermore, the rescuer and patient weight must not exceed the loading limit for the device[93]. Currently, safe loading for the edge of the platform should not exceed 750 N[93]. This equates to a rescuer weighing 76.4 Kg, which is marginally above the mean weight of the rescuers participating in these experiments. Rescuers exceeding this weight limit could potentially harm themselves and the patient.

5.4.7 Resuscitation Physiology

This research has identified a medical platform height of 48 cm, as the platform height at which quality of BLS was highest, and 68 cm and above demonstrated statistical significance for the depth of compression. However, statistical significance does not necessarily prove clinical significance. Translation into clinical practice needs to consider the physiological aspects of resuscitative techniques.

Chest compressions provide a transient circulation to the myocardium and refill a depleted left ventricle[48]. Physiological studies have demonstrated the depth of compression is directly related to the stroke volume (SV) and therefore cardiac output (CO)[29,37,158]. Translation of my study revealed platform height determined the depth of compressions achieved by trained BLS rescuers. Therefore, it is proposed platform height may impact on SV, cardiac output and therefore coronary perfusion pressure (CPP).

Furthermore interruptions to chest compressions caused by rescuer rotation and adjustments of platform height could have a physiological consequence for the patient[31]. The initiation of chest compressions does not cause an immediate elevation of CPP and coronary blood flow. Initially, a negative CPP will exist due to the right-sided pressures being higher than the left and ventricular interaction[159]. Initial chest compressions are necessary to reverse the negative CPP gradient. However once stopped chest compressions are stopped pressure falls and blood flow stops.

The physiological consequences of sub-optimal rescuer posture and poor quality resuscitation efforts may indicate manual delivery of chest compressions is not consistently achievable. A lower platform height is associated with improved performance but not necessarily achieving guideline rescuer posture. Furthermore, optimum posture is not always achievable despite a low platform height. The existing training and education programmes are not necessarily adequate for the physiological resuscitative requirements. Therefore studies using mechanical devices[160,161] may provide an alternative to manual chest compressions and eradicate the platform height issue for in-hospital cardiac arrests, as recommended for the cath lab environment[72]. However, a meta-analysis[162] has indicated that the use of mechanical devices for in-hospital cardiac arrests may improve survival outcomes but more randomised controlled trials are necessary because of poor quality evidence.

5.5 Future work

5.5.1 Platform Heights

Chapter 5 has highlighted the significance and translational aspect of platform height on chest compressions and the quality of BLS. It also presented the limitations of research and identified those areas to be explored further to maximise application to practice.

The experiments demonstrated a platform height of 68 cm and above are statistically more significant than lower heights. They also demonstrated a greater number of rescuers achieving the minimum depth of compression, for both experiments, at 48 cm, using 10 cm changes to platform height. Additional work, would consider an RCT with heights lower than 48 cm and evaluate smaller increments in platform height to provide more explicit guidance to policymakers and manufacturers of medical platforms. Experiments at lower platform heights could reveal the effects on rescuer posture and forces on the depth of chest compressions. Lower heights would encompass additional platforms employed within the health service. However, clinical trials using platform heights as a variable would need to consider the ethical issues related to resuscitation.

All clinical platforms regardless of purpose, including width[163] and platform compliance must consider the resuscitation environment. In-hospital platforms include bariatric beds, theatre trolleys, couches and catheter laboratory tables. Outside hospitals, ambulances employ stretchers to transport and treat patients[164,165]. Ambulance stretchers are not covered within the current British Standards[93] for medical platforms despite a review in 2007[166]. Studies into the effects of stretchers on resuscitation has advocated rescuers straddling the patient during BLS[167] which would address the posture issue but not the weight distribution. The physical dimensions of these platforms will alter rescuer posture and forces. All of which would provide more information to develop the FPJ or FJP[96] approach to chest compressions. Alternative medical platforms could be considered within the current geometrical (chapter 3) and forces concepts (chapter 4) to predict rescuer posture and forces.

5.5.2 Geometrical Model and Forces Concept

Development of the geometrical model and forces concept could enhance the application for the variety of hospital platforms, mentioned previously. The geometrical model has provided a fundamental mathematical model but would require development to consider the complexity of vertebrae, hip joints and elbows. All of which would support the development and applicability of the forces aspect.

The forces concept requires development to consider the kinetic activity related to upper body muscle groups and force. Surface Electromyograph (sEMG) could be used to investigate relevant muscle groups to determine active and inactive muscle groups. More importantly, identify muscle groups that are active, but ineffective due to altered rescuer posture caused by changes in platform height.

Other factors to be examined would include the effects of the rescuer's centre of mass (CoM) and spinal loading. The objective to improve the quality of BLS by identifying an optimum platform height, but the health of the rescuer must also be examined. Post-experiment feedback from rescuers would be required to discover the long-term effects of platform height on rescuer health. Further research into the loading of spines would be required to detect and quantify the loading for different platform heights. Feedback from rescuers following a new experiment would be required to document any injuries or pain long–term post experiments.

Further studies in the biomechanical laboratory would address many of the issues raised but should also include rescuer fatigue and skills retention. Studies exploring the effects of platform height and poor rescuer posture on rescuer fatigue would determine when fatigue starts to effect quality of chest compressions. This will further support the need for an optimum platform height. To coincide with further work, skills retention using different platform heights should also be included. To ensure a useful data set, increased rescuer volunteers would be necessary. An increased sample size to power a study to enhance interpretation of rescuer characteristics

The study population were considered representative of a BLS trained population working in an acute NHS trust. However, the demographics of the national resuscitation population would need to consider the number of female rescuers within the cardiac arrest environment. The impact of gender on the quality of chest compressions and platform height would need to be explicit for all rescuers[168].

Further work would need to consider the effects of time on the degradation of BLS skills and a potential relationship with inappropriate posture and platform heights. Furthermore, work would be required to document previous BLS training to establish the potential chronological degradation of psychomotor skills. Experiments over a longer period of time to explore learning and adaption of rescuers adopting a fit the job to the person approach or fitting the person to the job could provide a methodology.

5.5.3 Resuscitation Physiology Model

The aim of BLS is to provide an adequate transient circulation prior to more advanced life-saving techniques. During rescuer training, rescuers do not link the depth of chest compressions achieved to the quality of the resuscitation physiology i.e. CPP. Further development of the geometrical model and forces concept could incorporate a physiological model to visually demonstrate the quality of the rescuer's resuscitation performance. The physiological model could be configured to demonstrate the gradual quantitative increase in CO or CPP as BLS is initiated. In addition, the physiological model could demonstrate, the impact of platform height, the detrimental effects of interruptions, delay, poor depths of chest compressions and ultimately the probability of successful defibrillation.

5.5.4 Additional Resuscitation Scenarios

The work developed as part of this thesis could be used to investigate areas considered alternative or sub-optimal environments in resuscitation. These include pregnant patients, the aquatic environment and space travel. Currently resuscitation guidelines advocate the implementation of a Cardiff wedge for pregnant patients during BLS to alleviate pressure on the inferior vena cava. Combined with an inappropriate platform height, lives could be at risk. There is conflicting evidence related to aquatic resuscitation and the methodology of BLS[169,170]. To identify if effective BLS could be delivered in the aquatic environment or victim re-location is the greater priority. Investigations into performing BLS in a zero gravity environment will become more evident as space exploration continues.

Resuscitation was developed over 50 years[61] ago and guidelines are reviewed every 5 years. However, changes to guidelines have demonstrated a marginal improvement in survival from a cardiac arrest. The chain of survival[19,58,98] (

Figure 5-4) is only effective if each link in the chain is optimised with evidence based medical science and education[60]. This thesis provides an opportunity to improve the second link in the chain of survival.

Figure 5-4 Chain of Survival modified by author. Image reproduced with permission, Elsevier.

5.6 Conclusion

This programme of research has investigated a fundamental but critical aspect of in-hospital resuscitation and presented an opportunity to maximise the second link in the Chain of Survival (

Figure 5-4). Results are of notable clinical interest as they have demonstrated platform height is an important factor in depth of compressions achieved by rescuers over a range of clinically relevant platform heights. Findings provide evidence and clarity over existing contrasting studies and can be used to inform resuscitation guidelines and British Standards for medical platforms.

The research has presented a novel geometrical model to predict rescuer posture and a forces concept to derive the origins of rescuer forces. The model can be further developed to increase accuracy and improve understanding of this practical task. The model and concept could be used within resuscitation training programmes to increase awareness of the effects of platform height on resuscitation effort.

The series of investigations have demonstrated a platform height of 48 cm does not always permit rescuers to adopt the recommended posture. Depth of compression data have revealed a platform height below 68 cm is required in order to maximise performance. Therefore, a platform height of below 48 cm would address posture and quality aspects of BLS. Further work, encompassing heights lower than 48 cm could include additional medical platforms.

The height setting for all medical platform during a cardiac arrest should be set by British Standards and not dictated by manufacturers. British safety standards need to include the height setting for the CPR function on all medical platforms. It follows that resuscitation policymakers need to raise awareness of the impact of platform height on the depth of compression during BLS.

Translation of this simulation research into randomised controlled clinical trials could provide the evidence to develop resuscitation guidelines (ILCOR), inform national standards for all medical platforms, enhance resuscitation physiology and improve survival from in-hospital cardiac arrest. Patients' lives could be at risk from medical platforms that are positioned at a height inappropriate for the delivery of effective BLS.

Appendices

Appendix A Data Collection Sheet

Version 1.1

July 2010

CPR in Special Circumstances

Experiment 2

Laboratory Based (Spatial Relationship (platform height) – rescuer to victim)

Principal Investigator: Richard Bain Contact: r.bain@soton.ac.uk

Supervisors: Dr G Petley, Prof G Clough

SOM REC Ref NO: Bain230810.001 Ethics ApprovalSOMSEC064.10

Participant ID:

Please answer yes or no to the following.

1) Have you been BLS trained in the last 12 months? Yes/No
2) Did you pass this training? Yes/No
3) Are you fit and well? Yes/No
4) Do you have or ever had a back problem? Yes/No

Sex: M/F

Age: years

Weight: Kg

Height: cm

Appendix B Participant Information Sheet

Version 1.1

July 2010

CPR in Special Environments

Experiment 2

Laboratory Based (Spatial Relationship –rescuer to victim)

Principal Investigator: Richard Bain Contact: r.bain@soton.ac.uk

Supervisors: Dr G Petley, Prof G Clough

SOM REC Ref NO: Bain230810.001 Ethics ApprovalSOMSEC064.10

Participant ID:

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of this study?

Sudden cardiac death is a major public health problem. Cardiopulmonary resuscitation (CPR) is the immediate and effective intervention. The quality and timing of CPR is a significant predictor of outcome. The guidelines for the effective delivery of CPR assume the victim is supine and on a hard flat surface with the rescuer's shoulders positioned over the victim's chest. This may not be possible in non-standard scenarios, including road traffic accidents, confined spaces and in hospitals. It may also present the rescuer with a dilemma; to perform ineffective CPR or to delay CPR by re-locating the victim.

The purpose of this study is to establish whether effective CPR can be performed in the non-standard position

Why have I been chosen?

Appendix B

You have completed a BLS course in the last 12 months and have responded to our invitation. We plan to recruit up to 25 individuals to the study.

Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What will happen if I take part?

If you agree to participate you will be asked to attend the Gait Laboratory, Centre Block, E Level, Southampton General Hospital.

You will be asked to provide information about your age, height, weight and sex as well whether you regard yourself as fit and well. We will also ask you when you last received BLS training and did you pass this training?

On attending the Gait Laboratory you will be given a short reminder of the performance guidelines for CPR before undertaking the experiment. You will be attached to eight infrared motion sensors that will record your movement during the CPR. For the attachment of the sensors it would be preferable if you wore sports attire e.g. shorts and a T-shirt.

1 Palm (P)

2 Elbow (E)

3 Shoulder (S)

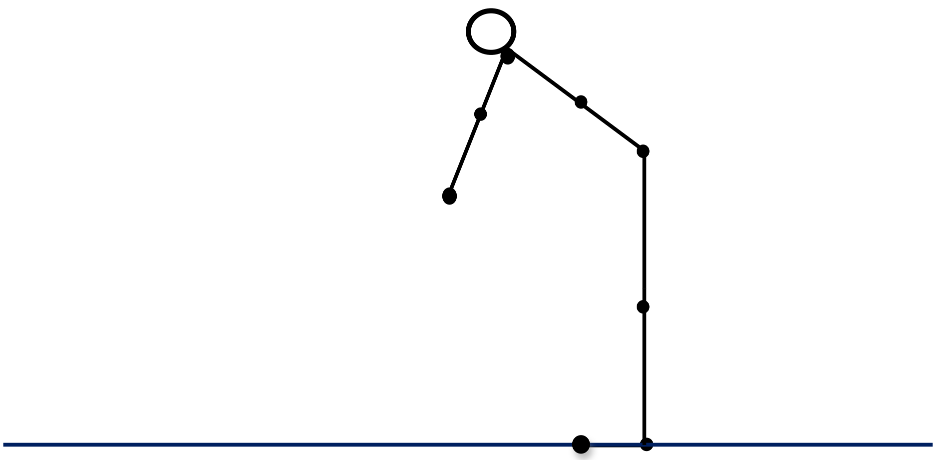
4 Mid Spine (Ms)

5 Hip (H)

6 Knee (K)

7 Ankle (A)

8 Toe (T)



For the purposes of this experiment you would be required to perform two cycles of chest compressions at the prescribed rate (100bpm) and depth (40-50mm) on a CPR manikin instrumented to record the depth and rate of compressions. The manikin will be in supine position during your rescue attempt on a bed at predetermined, but randomised heights. An audio tone will transmit beeps at rate of 100bpm to guide the rate of chest compression The CODA motion analysis system will be used to record the movement of the rescuer and determine the rescuer's position during the CPR. No life images will be obtained during the episode.

The whole study will take about 45mins.

What are the other possible disadvantages and risks of taking part?

We have identified no risks associated with this procedure if you are healthy. You will be excluded from the study if you have experienced back problems.

What are the possible benefits of taking part?

There are no clinical benefits to you as an individual from taking part in study. The information we gain will inform the future use of the technique in a range of rescue situations.

What if you have a concern or complaint?

The supervisor in charge of the project is Prof Clough (g.f.clough@soton.ac.uk) or Dr Petley (graham.petley@suht.swest.nhs.uk). You are free to contact either people if you have any concerns or complaint.

Will my taking part in the study be kept confidential?

All data will be anonymised using an identification code that is allocated upon recruitment. No volunteer personal details will be stored.

What will happen to the results of the research study?

We would hope to publish any new information in the scientific literature, to inform practice and to guide the functionality of hospital beds.

Who is organising and funding the research?

The study forms part of PhD project in the School of Medicine.

Appendix B

Who has reviewed the study?

This study has been reviewed and approved by the University of Southampton Research Ethics Committee.

Contact for further information:

Richard Bain
MP10
Education Centre
Southampton General Hospital
Tremona Road
Southampton
SO16 6YD

This information sheet should be kept together with your signed copy of the consent form.

Appendix C Participant Consent Form

Version 1.1

July 2010

CPR in Special Environments

Experiment 2

Laboratory Based (Spatial Relationship –rescuer to victim)

Principal Investigator: Richard Bain Contact: r.bain@soton.ac.uk

Supervisors: Dr G Petley, Prof G Clough

SOM REC Ref NO: Bain230810.001 Ethics ApprovalSOMSEC064.10

Please initial box

1. I confirm that I have read and understood the information sheet dated July 2010 for the above study and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.
3. I agree to take part in the above study.

Please initial each box

Name of Volunteer ____

Signature _______________________________ Date ________________________

Name of Person taking consent ____

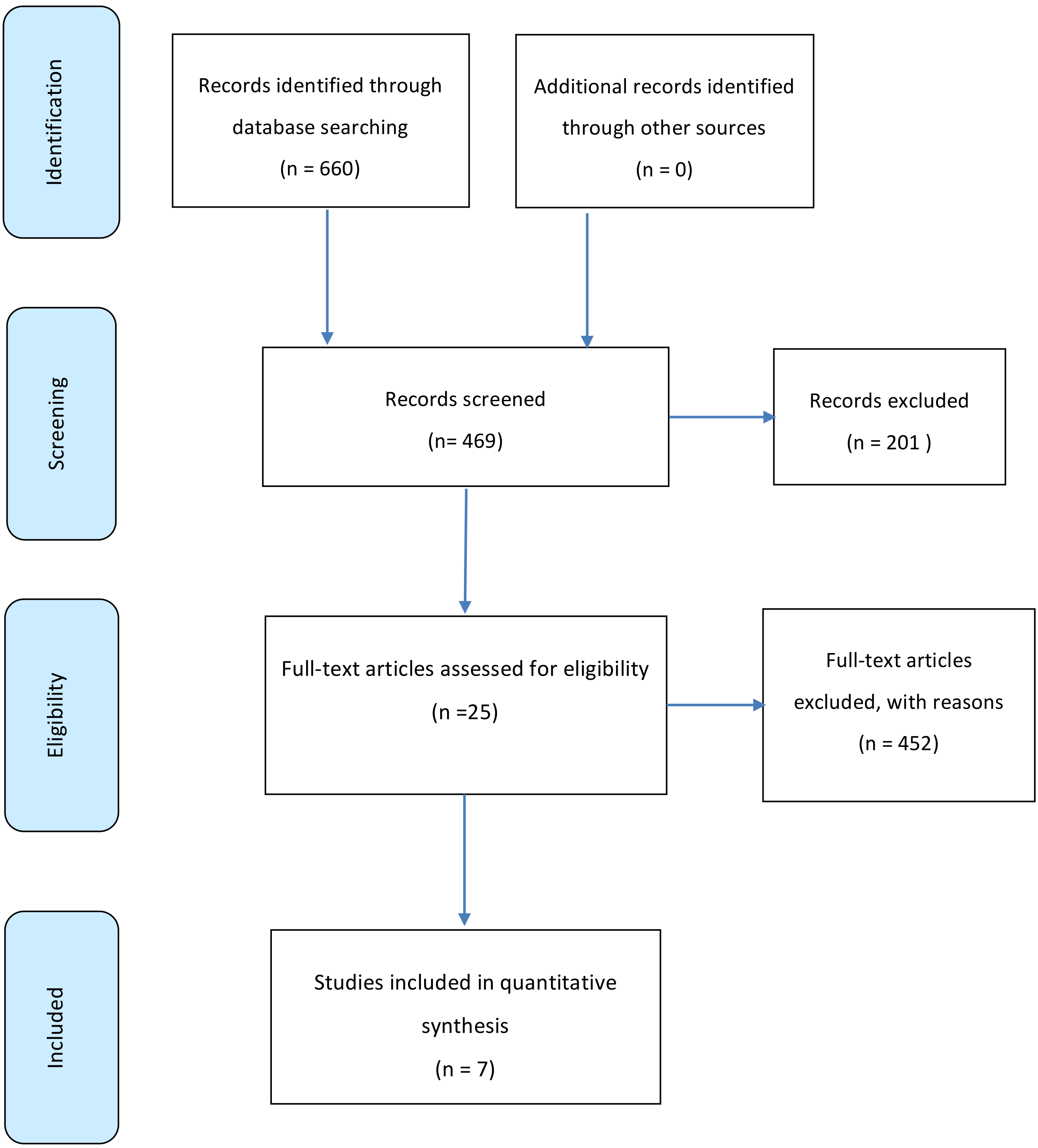
(if different from researcher)

Signature _______________________________ Date ________________________

1 copy for volunteer and 1 copy for researcher.

Appendix D PRISMA Flow Diagram

Delphis Search engine: Study selection Key terms; resuscitat*, Chest compress*, CPR, step stool, bed height, platform height, depth and compression.



Appendix E Ethics Letter – Chapter 3

UNIVERSITY OF Southampton

Mr Richard Bain
School of Medicine
MP10, Education Centre
Southampton General Hospital
Tremona Road
Southampton
SO16 6YD

RGO Ref: 7567

07 October 2010

Dear Mr Bain

Project Title Cardiopulmonary Resuscitation in Specila Circumstances - Part 2

This is to confirm the University of Southampton is prepared to act as Research Sponsor for this study, and the work detailed in the protocol/study outline will be covered by the University of Southampton insurance programme.

As the sponsor's representative for the University this office is tasked with:

1. Ensuring the researcher has obtained the necessary approvals for the study
2. Monitoring the conduct of the study
3. Registering and resolving any complaints arising from the study

As the researcher you are responsible for the conduct of the study and you are expected to:

1. Ensure the study is conducted as described in the protocol/study outline approved by this office
2. Advise this office of any change to the protocol, methodology, study documents, research team, participant numbers or start/end date of the study
3. Report to this office as soon as possible any concern, complaint or adverse event arising from the study

Failure to do any of the above may invalidate the insurance agreement and/or affect sponsorship of your study i.e. suspension or even withdrawal.

On receipt of this letter you may commence your research but please be aware other approvals may be required by the host organisation if your research takes place outside the University. It is your responsibility to check with the host organisation and obtain the appropriate approvals before recruitment is underway in that location.

May I take this opportunity to wish you every success for your research.

Yours sincerely

Dr Martina Prude
Head of Research Governance

Tel: 023 8059 5058
email: rgoinfo@soton.ac.uk

Corporate Services, University of Southampton, Highfield Campus, Southampton SO17 1BJ United Kingdom
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Appendix F Ethics Letter Chapter 4

Medicine

UNIVERSITY OF Southampton

24 January 2012

Re: 901 - CPR in Special Circumstances

Dear Dr Bain,

Thank you for submitting your application relating to the above project. I am pleased to inform you that full approval has now been granted by the Faculty of Medicine Ethics Committee.

Approval is valid from 2 January 2012 until 4 June 2012, which is the end date specified in your application. We will be in touch with you again in June 2012 to confirm that your project has been completed.

Please note the following points:

- the above ethics approval number must be quoted in all correspondence relating to your research, including emails;
- if you wish to make any substantive changes to your project you must inform the Faculty of Medicine Ethics Committee as soon as possible.

Please note that this letter will now constitute evidence of ethical approval. We wish you well with your research.

Yours sincerely

Professor John Holloway
Faculty of Medicine Ethics Committee

Glossary of Terms

Basic Life Support – delivery of chest compressions and rescue breathing during a cardiac arrest.

Cardiac Arrest – cessation of the electrical and mechanical cardiac activity**.**

Cardiopulmonary resuscitation – delivery of emergency treatment comprised of Basic Life Support and electrical defibrillation.

Coronary perfusion pressure – the difference between aortic diastolic pressure and right atrial pressure.

Depth of compression – peak depth of compression minus the residual depth of compression

Leaning – resting rescuer body weight against the manikin

Leanpush – combination of rescuer leaning and pushing their upper body against manikin

Moment -

Peak depth of compression – The maximum depth of compression

Pushing – rescuer pushing against the manikin with their upper body.

Residual depth of compression – the depth if compression during decompression

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