final report

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Biomechanics of boning a hind beef quarter

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Contents

1 Background and Aims of the Project

Initially the main aim of this project was to collect biomechanical data solely on the ‘H-boning’ and ‘knuckle pulling’ tasks associated with the boning of a hind beef quarter. The primary reason for collecting this biomechanical information was so that it could be used to aid in the development of a cobotic device designed to assist in boning beef. As a result, the initial project brief was to collect 3D kinematic (movement) data and the forces required by the knife to bone the Hbone and knuckle sections. However, after a visit by the ‘cobotics team’ (Professor Edward Colgate and Professor Michael Peshkin from Northwestern University: IL, USA) in January 2007, the main aims of the study were changed in response to the observations of the boning tasks. During that visit by the cobotic team, it was considered that the forces in the hook hand were more likely to result in overuse injury and thus the biomechanics project was altered to reflect this judgment. As a result, the main goal of the biomechanics project was changed to focus on the collection of dynamic hook forces during the H-boning and knuckle pulling tasks and to collect 2D kinematic data relevant to the development of a cobotic device. As a consequence of these changes to the aim of the experiment it was agreed that as part of this biomechanics project a device to measure hand force would be constructed and handed over to the research division of Meat and LivestockAustralia (MLA).

Whilst the requirements of this biomechanics project were to collect data exclusively from the H-boning and knuckle pulling tasks, I felt that the cobotics team would not be able to set the specifications of the cobotics device without information collected during the boning of all sections of the hind beef quarter. Therefore, I extended the project to collect data from the boning of all nine sections of the hind beef quarter, including the; 1.Thin skirt, 2.Tenderloin, 3.Loin, 4.H-Bone, 5.Rump, 6.Knuckle, 7.Topside, 8.Silverside and 9.Shank. This biomechanics project was also extended to collect kinetic cutting forces experienced by the knife during these tasks, so as to give a more balanced analysis of the forces involved in the boning process.

Thus, the main aims of this biomechanical project were to:

1. Design and construct a fully dynamic and portable system for measuring and recording the forces in the hands (hook and knife) during boning tasks.
2. Collect and analyse kinetic hand force (hook and knife) data during the boning of the nine sections of the hind beef quarter.
3. Collect and analyse 2D kinematic data in the sagittal plane during the boning of the nine sections of the hind beef quarter.
4. Collate the biomechanical kinetic and kinematic data for the cobotics team and report on the findings.

2 Methodology

2.1 Experimental protocol

All biomechanical data was collected using one experienced (34 yrs in the meat processing industry) boner (49 yrs, 98 kg and 171 cm tall) who boned three sides of beef into nine sections. These nine sections included:

1. Thin skirt
2. Tenderloin
3. Loin
4. H-Bone
5. Rump
6. Knuckle
7. Topside
8. Silverside
9. Shank.

The three hind quarters used in this project were considered of average size. The total weight of the meat processed from each of the three hind beef quarters averaged 48 kg. Whilst there are numerous ways to bone a side of beef, no specific instructions were given to the boner involved in the study on what technique they were to use to bone the hind beef quarter.

2.2 Data Collection

Kinetic (force) data was collected at 50 Hz (50 frames per second) using custom made data collection hardware and software. Both the hook and the knife were custom made and instrumented with force transducers. After calibration, the voltage levels from these instrumented devices were converted to Newtons and recorded at 50 Hz using the custom software.

Kinematic (motion) data was also collected at 50 Hz, which was synchronised with the collection of the kinetic data. Two cameras were placed orthogonal to the sagittal plane of the test subject so as to collect the sagittal plane kinematics from both the hook (left hand) and knife (right hand) sides. Reflective markers were also placed over the major anatomical landmarks of the upper body so that these could be tracked during post data processing.

2.3 Data Analysis

Kinematic data were filtered using a dual pass 2nd order Butterworth low pass filter with a cut-off frequency of 6 Hz to remove noise resulting from movement artefact. From the tracked displacement data, velocity and acceleration were calculated and descriptive statistics were determined. As well as the normal descriptive statistics obtained from the raw kinetic data, the impulse (area under the force time curve) was also calculated to give an estimate of the ‘volume’ of force required by each hand during the nine boning tasks analysed.

3 Results

The average total 'cutting' duration (i.e. not including the rest time between the boning of each of the nine sections) required to bone the rear section of the beef was approximately 6 minutes. The relative and absolute time spent boning each of these nine sections and the respective average yield is given in Table 1.

Table 1: Absolute and relative durations and weights associate with each of the nine segments of the hind beef quarter boning task.

	Duration		Weight	
	Absolute (s)	Relative (%)	Absolute (kg)	Relative (%)
1. Thin Skirt	27 (2)	7.3	4.2 (0.3)	8.8
2. Tenderloin	34 (7)	9.3	2.2 (0.3)	4.6
3. Loin	26 (14)	7.1	5.0 (0.6)	10.5
4. H-Bone	92 (7)	25.2	2.0 (0.1)	4.3
5. Rump	9 (1)	2.4	5.5 (0.4)	11.6
6. Knuckle	71 (21)	19.5	4.8 (0.7)	10.1
7. Topside	46 (5)	12.6	9.0 (0.9)	18.9
8. Silverside	29 (2)	8.0	9.3 (0.8)	19.6
9. Shank	31 (4)	8.6	2.3 (0.4)	4.8
Bones remaining			3.2 (0.4)	6.7
Total	365 (51)		47.5 (2.4)	

The H-bone and knuckle sections took the longest times to remove; 92 s and 71 s respectively. All other sections (with the exception of the rump which was removed very quickly) took similar times to bone, between 26 and 46 seconds. Whilst the topside and silverside sections yielded the greatest amount of meat (by weight), it is difficult to compare the true values of the meat yielded from each section as each section has different market values.

3.1 Kinetics

3.1.1 Hook kinetics

The forces in the hook (pulling) hand were generated predominantly when the hook was pulling the meat and periostium (connective tissue covering the bone) away from the bone; or alternatively during the H-boning task when the bone was being pulled away from the meat. These pulling forces could be present for substantial periods when the boner needed to open up a section so that the knife could 'get into' a confined space to cut away a containing ligament for example. In these situations, not only are the maximum puling forces large but the impulse (volume) of the pulling force is also high. Alternatively, large peak forces in the hook were experienced when the hook was used in a flicking fashion to rip the meat from the bone (e.g. when removing the tenderloin section). The collated pulling forces experienced in the hook hand for each of the nine boned sections is summarised in Table 2.

Table 2: Maximum and average pulling forces and the impulse applied by the hook whilst boning each of the nine segments of the hind beef quarter.

	Max Force (N)	Average Force (N)	Impulse (Ns)
1. Thin Skirt	104 (15)	13 (7)	384 (184)
2. Tenderloin	258 (7)	86 (1)	2925 (807)
3. Loin	167 (31)	8 (1)	206 (109)
4. H-Bone	313 (85)	72 (19)	6518 (1484)
5. Rump	217 (43)	94 (32)	797 (216)
6. Knuckle	306 (31)	62 (3)	4407 (1292)
7. Topside	370 (42)	118 (6)	5418 (476)
8. Silverside	295 (53)	87 (18)	2605 (451)
9. Shank	210 (29)	27 (4)	874 (147)
Overall	370 (83)	63 (39)	24134 (2165)

The maximum pulling force exerted in the hook across all trials and all nine segments was 370 N, which occurred whilst pulling the topside section down. A similar level of force was present when boning almost all nine segments. These high forces measured when boning all segments indicates that at some point in every boning task substantial forces are required to be generated by the hook hand of the boner. However, examination of the average force data indicates that whilst a maximum force between 200 N and 300 N was present for most segments, the duration over which the force was applied was significantly different. For example, whilst the maximum force exerted by the hook when boning the H-bone and shank segments was similar, the pulling force in the hook was sustained for longer periods when boning the H-bone (72 ± 19 N) as compared to when boning the shank (27 ± 4 N) segment; as is shown by the average force data. (Note: the average force data includes the 0 N force that occurs when the hook is not being used).

The impulse data presented in Table 2 represents not only the forces produced by the hook but the duration over which these forces are applied. As a result, the impulse data is the best indicator of the volume of force experienced by the boner in the hook hand, and thus is a better indicator of the relative risk of a cumulative injury occurring than either maximum or average force data. From an examination of the impulse data, boning the H-bone, topside and knuckle sections pose the greatest risk of musculoskeletal injury due to the high exposure to substantial exertion levels over prolonged durations. The boning of the tenderloin and silverside sections also experienced noteworthy exposure to musculoskeletal injury due to the pulling exertion required. The rate at which force needs to be produced is also a factor that influences the risk of musculoskeletal injury, as the greater the rate of force production the higher the contraction velocity and strain rate on the musculo-tendonis tissues. The maximum pulling force rate experienced in the hook during all boning tasks analysed was 425 Ns-1. The profiles of the hook forces generated whilst boning each of the nine sections for each of the three trials is presented in the Appendix.

3.1.2 Knife kinetics

It was assumed that if the knife is sharp then the forces experienced when slicing through muscle should be relatively low. However, substantial cutting forces were measured in the knife hand. These cutting forces generated in the knife were most prevalent when the knife was used to 'score' the bone (i.e. cut the periostium so that the meat can be ripped from the bone with maximum yield), or when cutting tendons. These cutting forces were particularly prevalent when cutting the tenderloin, loin, H-bone and knuckle sections. The collated cutting forces experienced in the knife hand for each of the nine boned sections is summarised in Table 3.

Table 3: Maximum and average cutting forces and the impulse applied by the knife whilst boning each of the nine segments of the hind beef quarter.

	Max Force (N)		Average Force (N)		Impulse (Ns)	
1. Thin Skirt	65	(13)	3	(1)	78	(20)
2. Tenderloin	149	(3)	12	(11)	359	(271)
3. Loin	120	(17)	11	(2)	264	(99)
4. H-Bone	272	(3)	31	(9)	2891	(1046)
5. Rump	85	(34)	9	(7)	74	(53)
6. Knuckle	181	(13)	9	(3)	589	(11)
7. Topside	156	(20)	6	(4)	251	(158)
8. Silverside	41	(20)	1	(1)	4	(12)
9. Shank	129	(4)	15	(3)	464	(72)
Overall	272	(69)	11	(9)	4974	(759)

The maximum cutting force exerted in the knife across all trials and all nine segments was 272 N, which occurred whilst boning the H-bone. There were also sizeable cutting forces experienced in the knife whilst boning much of the hind beef quarter, particularly those segments with a lot of bone contact (e.g. the H-bone and knuckle sections). A visual analysis of kinematic data matched to the kinetic knife data indicated that high cutting forces occurred whilst 'scoring' along a bone section to cut through the periostium or when cutting through a tendon. As these periods of high knife force were generally of short duration, the average knife forces were significantly less than the average hook forces (Figure 1). Similar to the average forces, the impulses experienced in the knife hand were significantly less than those experienced in the hook hand (Figure 2). However, the average impulse in the knife hand whilst removing the H-bone in each of the three hind quarters used was considerable (2891 ± 1046 Ns-1). The relatively high impulse in the knife hand during the H-bone removal task occurred because there was a lot of contact between the knife and the bone over relatively long durations. The maximum rate at which the cutting force was applied by the knife during all the boning tasks analysed was 389 Ns-1. The profiles of the knife forces generated whilst boning each of the nine sections for each of the three trials is presented in the Appendix.

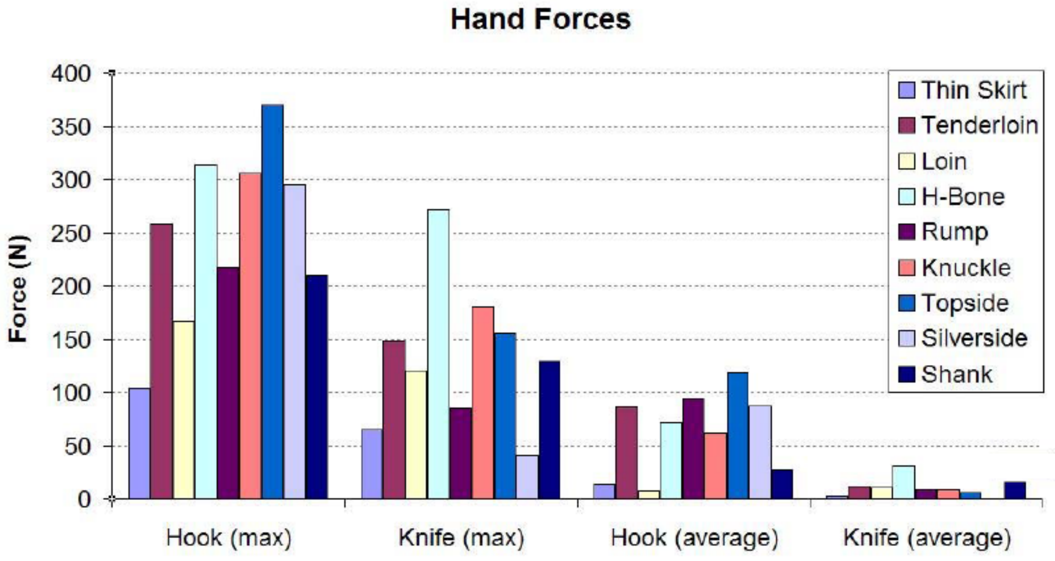


Figure 1: Comparisons of maximum and average forces for the hook and knife hands when boning each of the nine sections of the beef hind quarter.

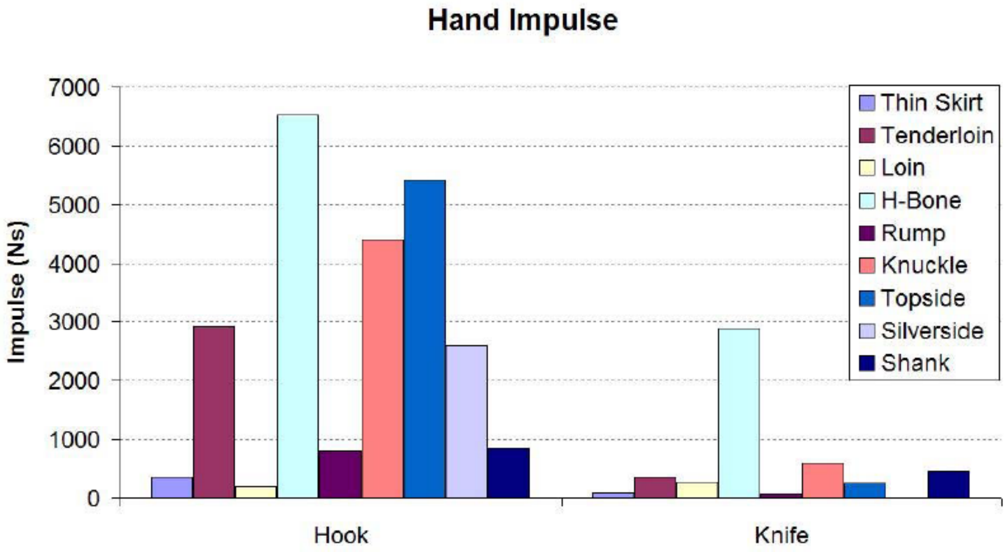


Figure 2: Comparisons between impulses for the hook and knife hands when boning each of the nine sections of the beef hind quarter.

Detailed comparisons of the hand forces (hook and knife) experienced in each of the three trials (for each of the nine sections) are presented in the Appendix. As a general rule, the temporal pattern and the magnitude of the applied hand loads are quite similar for each of the three trials. However, care must be taken in applying this data to all boners, as all trials were performed by the same person who may have a very different boning technique from other boners.

3.2 Kinematics

The 2D sagittal plane kinematic data was collected and synchronised with the kinetic data. (Note: for a visual presentation of the tracked kinematic hand data synchronised with kinetic data see the electronic files accompanying this report).

The trajectories of both hands were tracked and the displacement, velocity and acceleration were calculated. The minimum and maximum range in both the horizontal and vertical direction from the hook holding the meat was calculated for each of the nine segments, and the maximum velocity and acceleration was also calculated; which are presented in Table 4 (hook) and Table 5 (knife).

Table 4: Kinematic data for the hook hand for each of the nine segments relative to the hook holding the hind beef quarter.

Hook Kinematics	Horizontal			Vertical		
	Range (cm)	Max Velocity ($cm.s^{-1}$)	Max Acceleration ($cm.s^{-2}$)	Range (cm)	Max Velocity ($cm.s^{-1}$)	Max Acceleration ($cm.s^{-2}$)
1. Thin Skirt	6 – 112	148	623	66 – 122	104	732
2. Tenderloin	4 – 88	110	1146	79 – 128	212	2262
3. Loin	2 – 81	86	474	40 – 139	330	1287
4. H-Bone	6 – 122	81	314	32 – 137	243	1016
5. Rump	38 – 64	65	483	80 – 114	40	350
6. Knuckle	11 – 68	65	223	31 – 122	235	1715
7. Topside	5 – 57	37	149	37 – 112	124	623
8. Silverside	9 – 80	40	222	27 – 105	119	699
9. Shank	-5 – 45	58	341	-2 – 73	208	905
Overall	-5 – 122	148	1146	-2 – 139	330	2262

Table 5: Kinematic data for the knife hand for each of the nine segments relative to the hook holding the hind beef quarter.

Knife Kinematics	Horizontal			Vertical		
	Range (cm)	Max Velocity ($cm.s^{-1}$)	Max Acceleration ($cm.s^{-2}$)	Range (cm)	Max Velocity ($cm.s^{-1}$)	Max Acceleration ($cm.s^{-2}$)
1. Thin Skirt	2 – 104	94	596	47 – 156	167	1010
2. Tenderloin	4 – 63	118	454	46 – 144	299	1137
3. Loin	2 – 74	206	1140	62 – 162	94	545
4. H-Bone	-8 – 60	92	449	41 – 119	165	847
5. Rump	11 – 64	44	447	56 – 93	72	233
6. Knuckle	0 – 75	80	301	16 – 109	249	1231
7. Topside	1 – 41	48	229	18 – 71	129	686
8. Silverside	5 – 38	44	441	20 – 64	135	454
9. Shank	-10 – 35	68	261	7 – 91	317	1093
Overall	-10 – 104	206	1140	7 – 162	317	1231

The overall displacement of both the hook and knife hands in the sagittal plane was similar in both the vertical and horizontal directions. There was however some variation between the displacement data for some segments. Using the hook holding the beef quarter as a reference point (and with a positive number reflecting displacement towards the boner), the displacement of either hand ranged from approximately -10 cm to 160 cm (see Figures 3 and 4). Although most of the horizontal displacement occurred when the hand was lower (i.e. when vertical displacement was high). (Note: for a more detailed visual representation of the temporal hand trajectories for each segment see the electronic video analysis files submitted with the report).

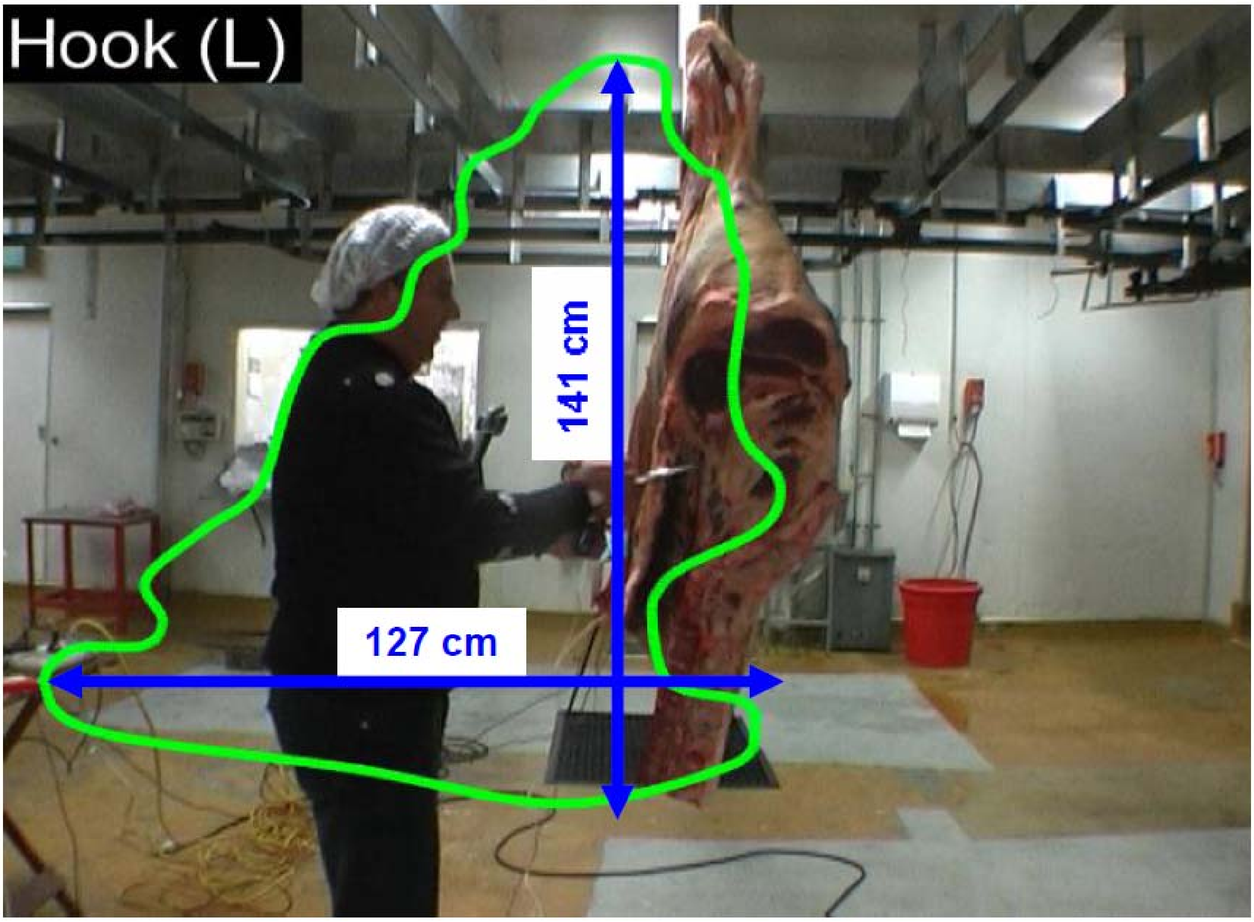


Figure 3: Total displacement of the hook hand when boning all nine segments of the hind beef quarter. The outline of the maximum displacement of the hook hand for all nine segments is shown in green, whilst the horizontal (127 cm) and vertical (141 cm) ranges are shown in blue. (Note: the hook was held in the left hand but this picture was mirrored to aid in the visual comparison with the knife hand).

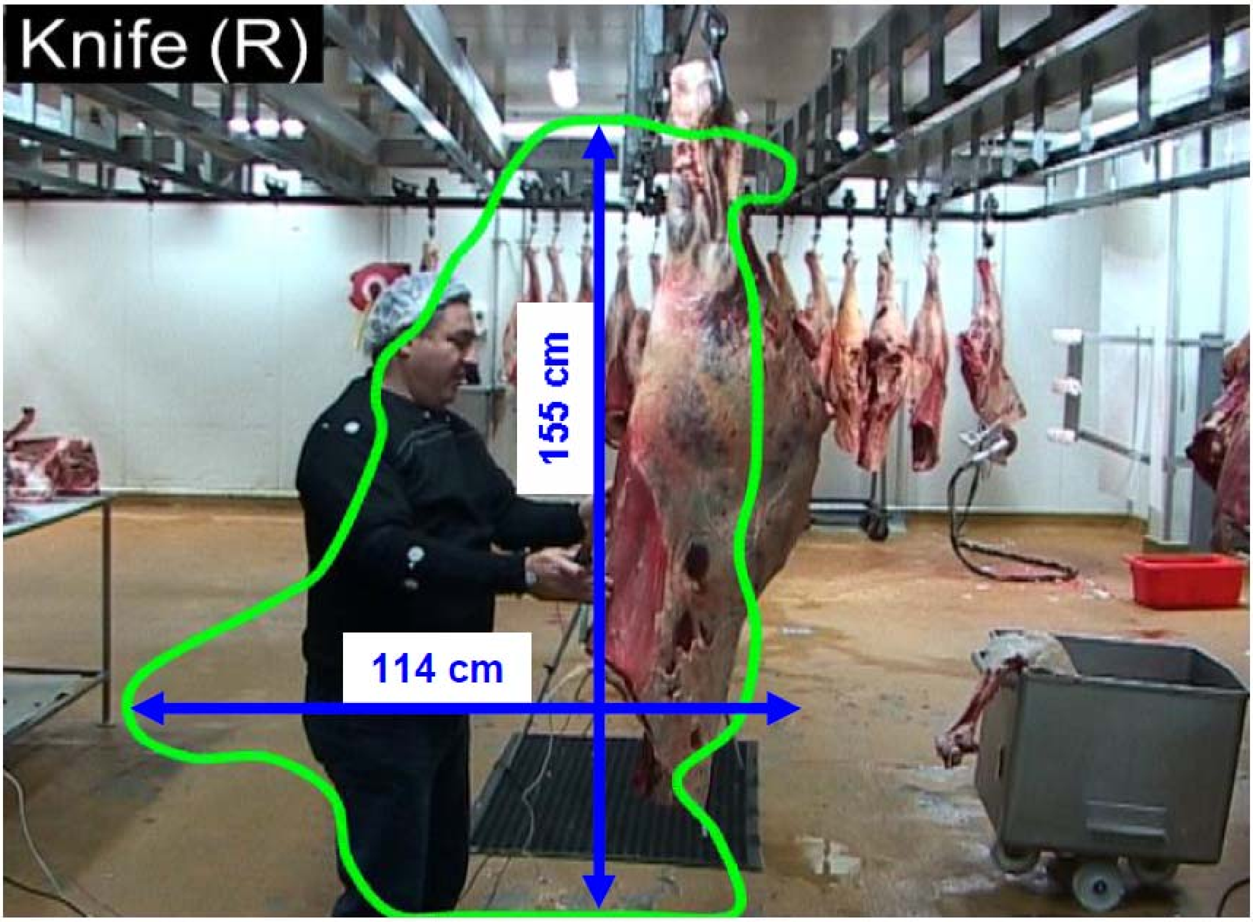


Figure 4: Total displacement of the knife hand when boning all nine segments of the hind beef quarter. The outline of the maximum displacement of the hook hand is shown in green whilst the horizontal (127 cm) and vertical (141 cm) ranges are shown in blue.

In comparison to the similarities in the displacement data, the velocity and accelerations of both hands differed in the horizontal and vertical directions. Although there was some variation for the various segments, on average the velocity and acceleration for both the hook and knife were approximately twice as high in the vertical as compared to the horizontal direction. The early boned segments (e.g. the tenderloin section) tended to have higher vertical hook kinematics as the hook was used to 'flick' the meet off the bone in a downward direction. For the later sections, the vertical hook velocities and accelerations were larger than in the horizontal direction because the meat was being pulled downwards rather than outwards from a high vertical position. Although the difference between the horizontal and vertical knife kinematics were not as large as for the hook, the vertical cutting velocities and accelerations tended to be slightly higher than in the horizontal direction due to the dominance of the downward applied cuts.

114 cm

4 Discussion

It was expected that the maximum pulling forces would be reasonably substantial during most of the boning tasks. However, what was not expected was that the maximum forces in the knife hand, although not as large as the hook hand, were still quite significant. These forces in the knife hand however were not sustained for long durations. From an examination of the magnitude and duration of the force applied to each hand (i.e. the impulse), the exposure to musculoskeletal injury is substantially greater for the hook as compared to the knife hand. However, when examining the level of musculoskeletal injury risk exposure, the repetitive nature of the task, the cold environment and awkward postures required also need to be considered; particularly with respect to the size of the small musculoskeletal tissues of the hand and forearm bearing the majority of the load. The boner was required to move the knife over a large vertical range (from 7 to 162 cm from the meat hook), which resulted in a bent over posture at the low boning heights (trunk flexion of 104 degrees) and with a fully extended reach of the upper arm at maximum height. Whilst the boner in this task was not particularly tall (171 cm) a taller person would still be required to perform a significant amount of over head work and might even have larger trunk flexion required whilst boning the lower beef sections. The flexed position of the trunk would place the boner at increased risk of injury to the lumbar spine, whilst over head work places the boner at increased risk of injury to the shoulder. These risks of musculoskeletal injury may also be exacerbated by the cold environmental working conditions.

The large forces in the knife primarily occur when ‘scoring’ the bone. These ‘scoring’ movements cut the periostium so that the boner can increase the yield by ‘cleanly’ pulling the meat away from the bone with the hook (i.e. periostium and all). Significant speeds and hand positions were also present in the knife hand, whilst the hook hand generally generated sustained forces with a lower dynamic component. However, significant speeds in the hook hand also occurred when ‘flicking’ the meat off the bone.

All of the data obtained in this experiment was performed using medium sized carcases. Substantial increases in force and reach are likely when boning large carcass sides, particularly bulls. All data was obtained using the same boner, and so whilst quite similar movement patterns were observed (even when boning the right or left sides) care must be taken in using this data to set the specifications of a cobotic device as other boners may use different boning techniques.

5 Recommendations

The major musculoskeletal risk factors for this task are:

1. The large forces experienced in both hands, resulting in increased injury risk for the upper limbs.

2. The large range of movement required in the task, which results in awkward postures for the lumbar spine and shoulder. However, these awkward postures are typically not sustained for long durations.

3. The speed, duration and repetitive nature of the working environment results in few rest breaks, which can result in cumulative reduction in the functional capacity of the musculoskeletal tissues over the working period. This is further exacerbated by the cold working environment.

Any intervention designed to reduce the risk of musculoskeletal injury during the boning task should aim to reduce the physical demands placed upon the upper limbs and/or improve the musculoskeletal tissue tolerances. In order to reduce these stated risks the following factors should be considered:

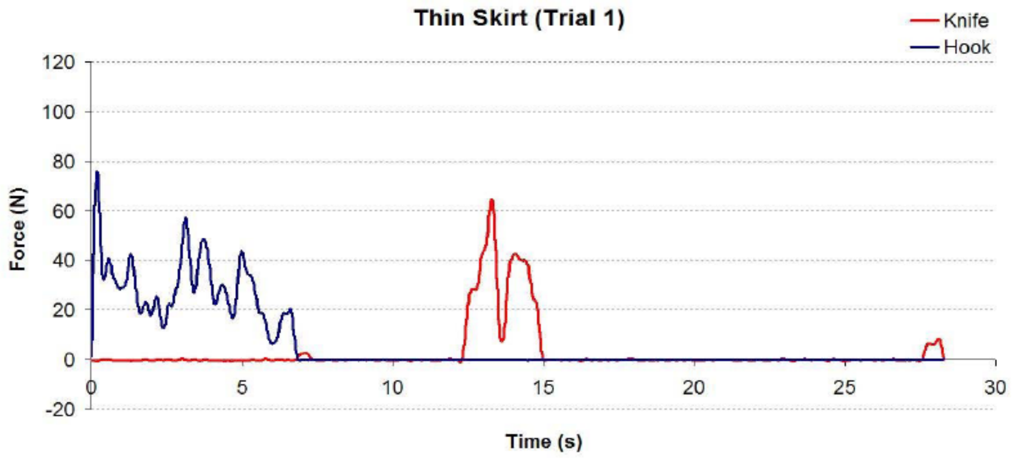
1. The cobotic device should be designed to reduce the forces required by the hands. However, this device would still need to be very dynamic and flexible so as to accommodate the wide variety of boning movements. The sensory feedback of the forces through the hands to the boner would also need to be maintained as this is how they know when to adjust their movements.

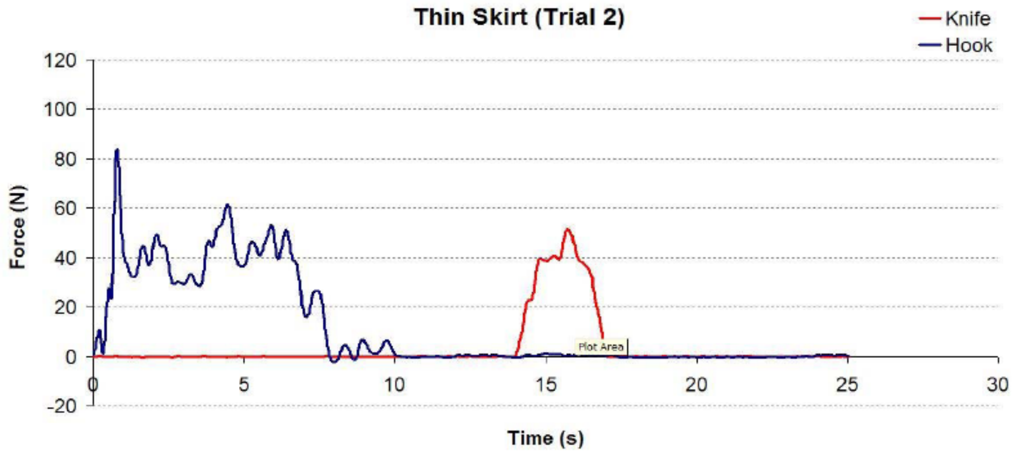
2. The task and/or working environment should be altered so that the boner has more control over the speed of the task.

3. The cold conditions should be examined to see if there is a way to reduce the risk of injury on the boner.

4. The final and most important recommendation is to involve the boners in the development of controls (including any cobotic device) in a participatory ergonomic process. This participatory process has two main advantages; firstly it ensures that all conditions of the task are considered and that the best controls are developed as the boners are the task experts and thus can have substantial knowledge to aid in the development of effective controls. The second, and equally important factor, is that the adoption of any developed controls by the boners will be substantially greater if they participate in the development of these controls.

6 Appendix - Kinetic Force Graphs of the Hook and Knife for all nine sections and all three trials





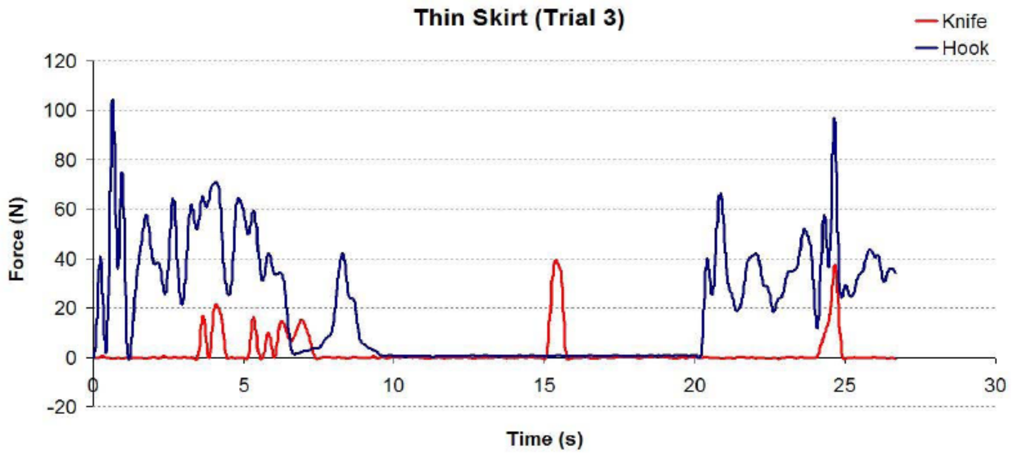
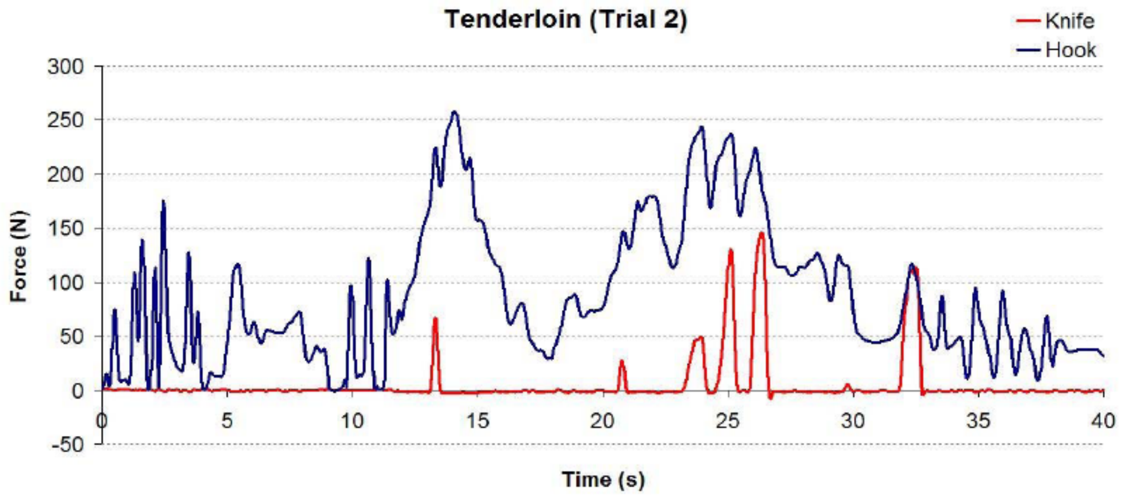


Figure A1: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the thin skirt section.



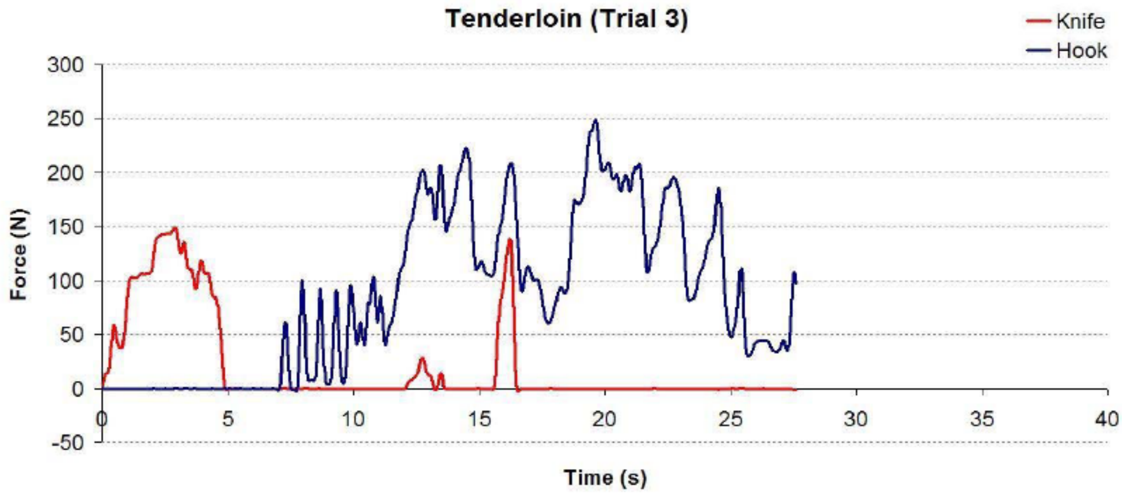


Figure A2: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, and 3) whilst boning the tenderloin section. (Note: No data wa collected for the first tenderloin trial due to technical problems durin data collection).

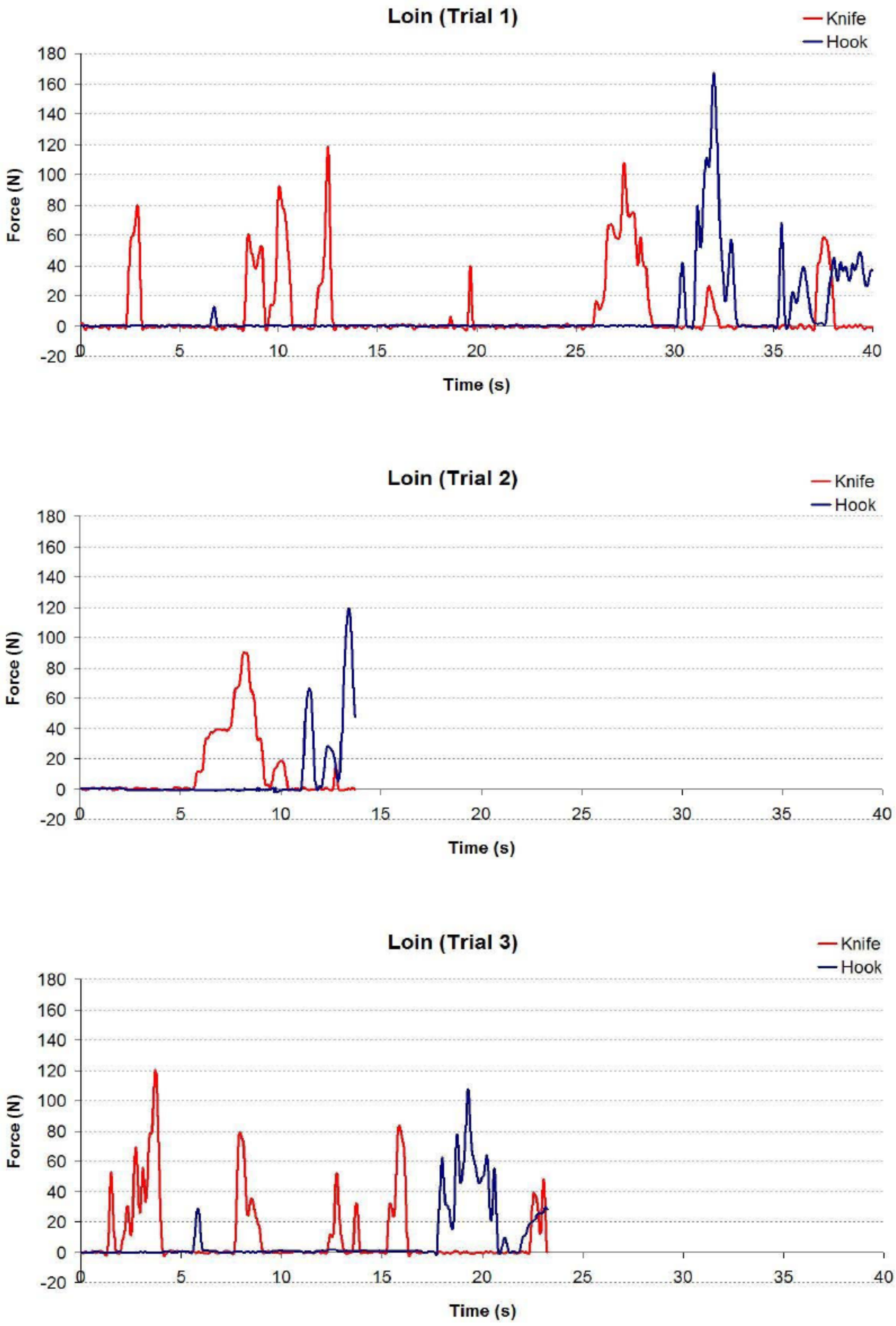


Figure A3: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the loin section.

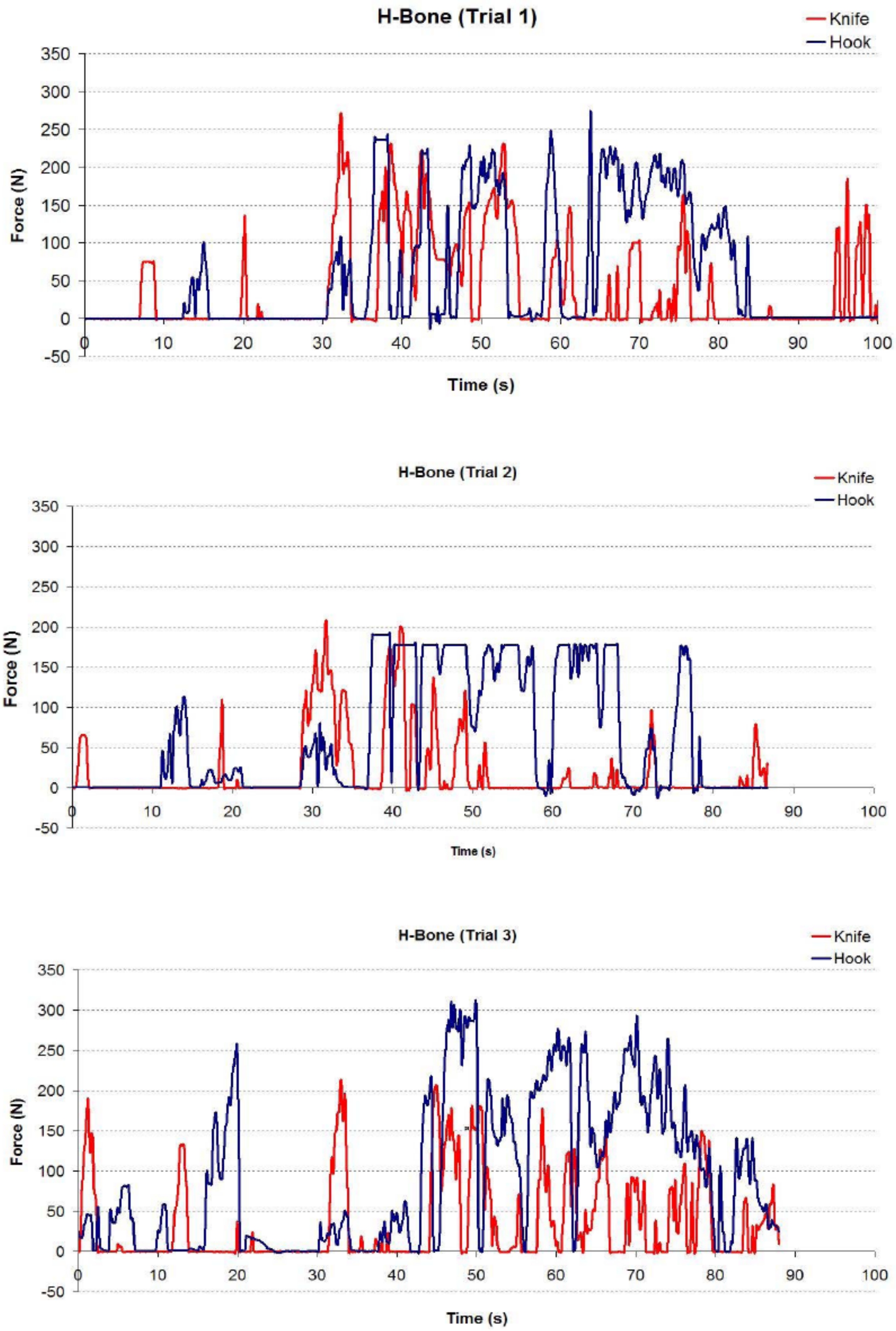


Figure A4: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the H-bone section.

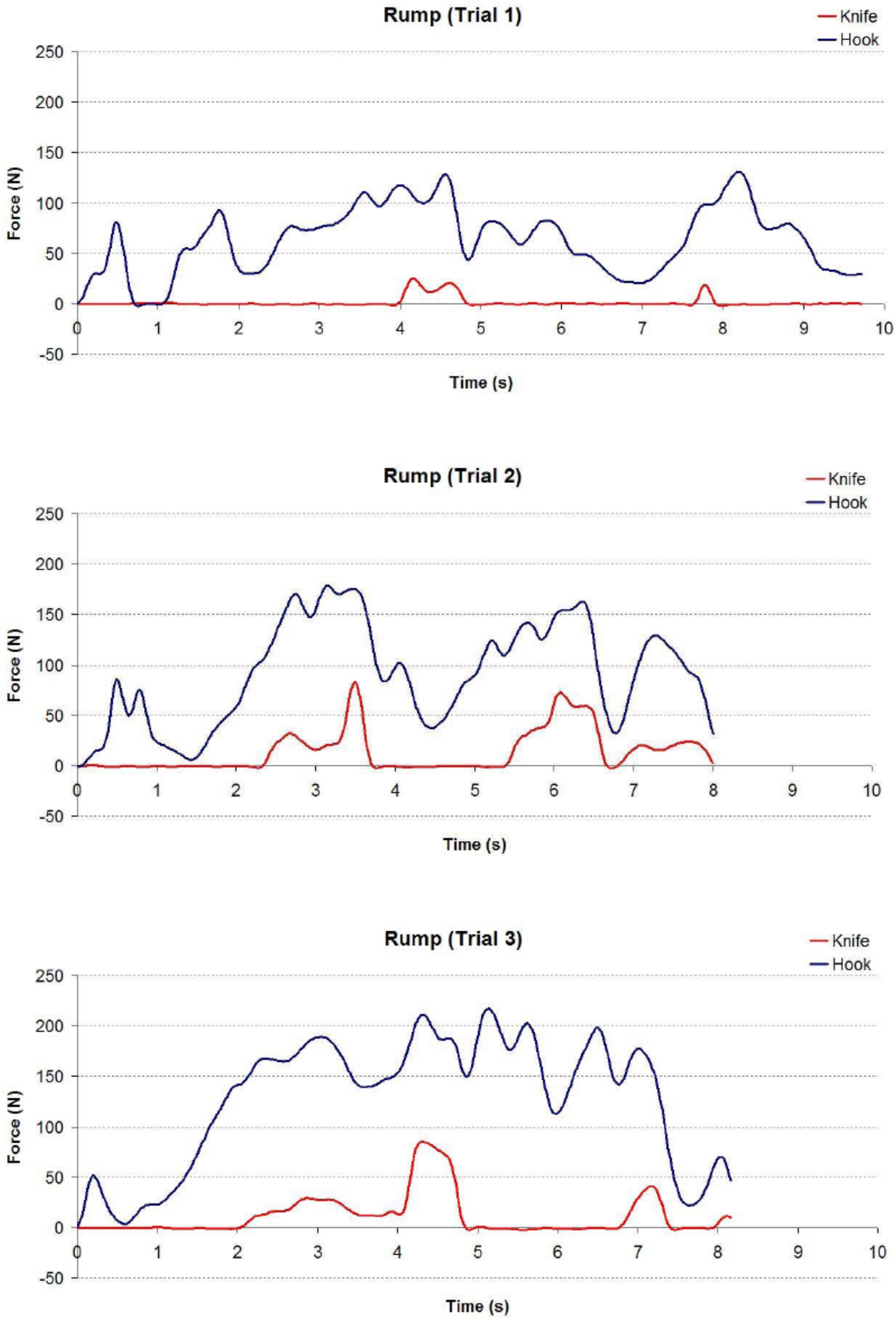


Figure A5: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the rump section.

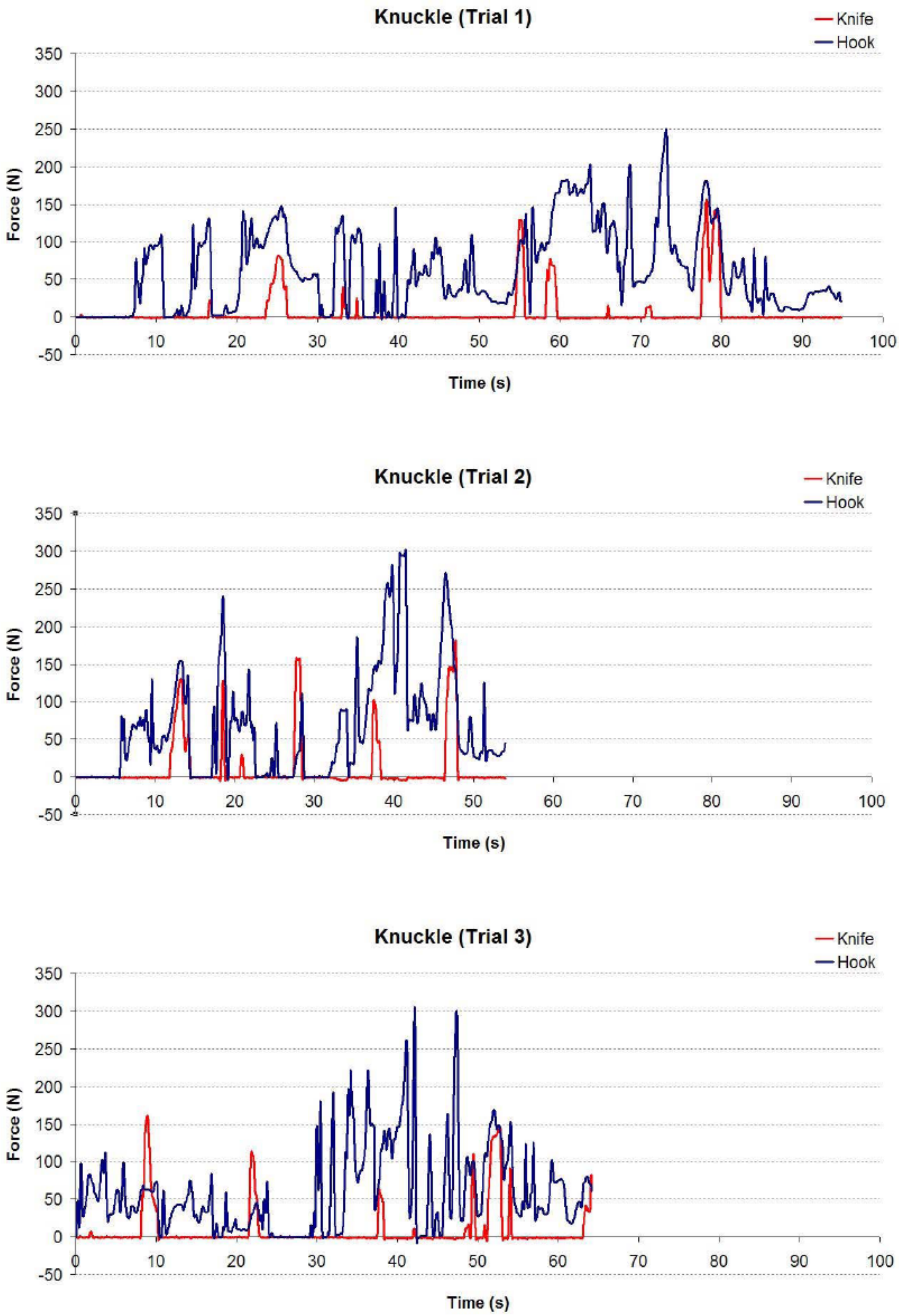


Figure A6: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the knuckle section.

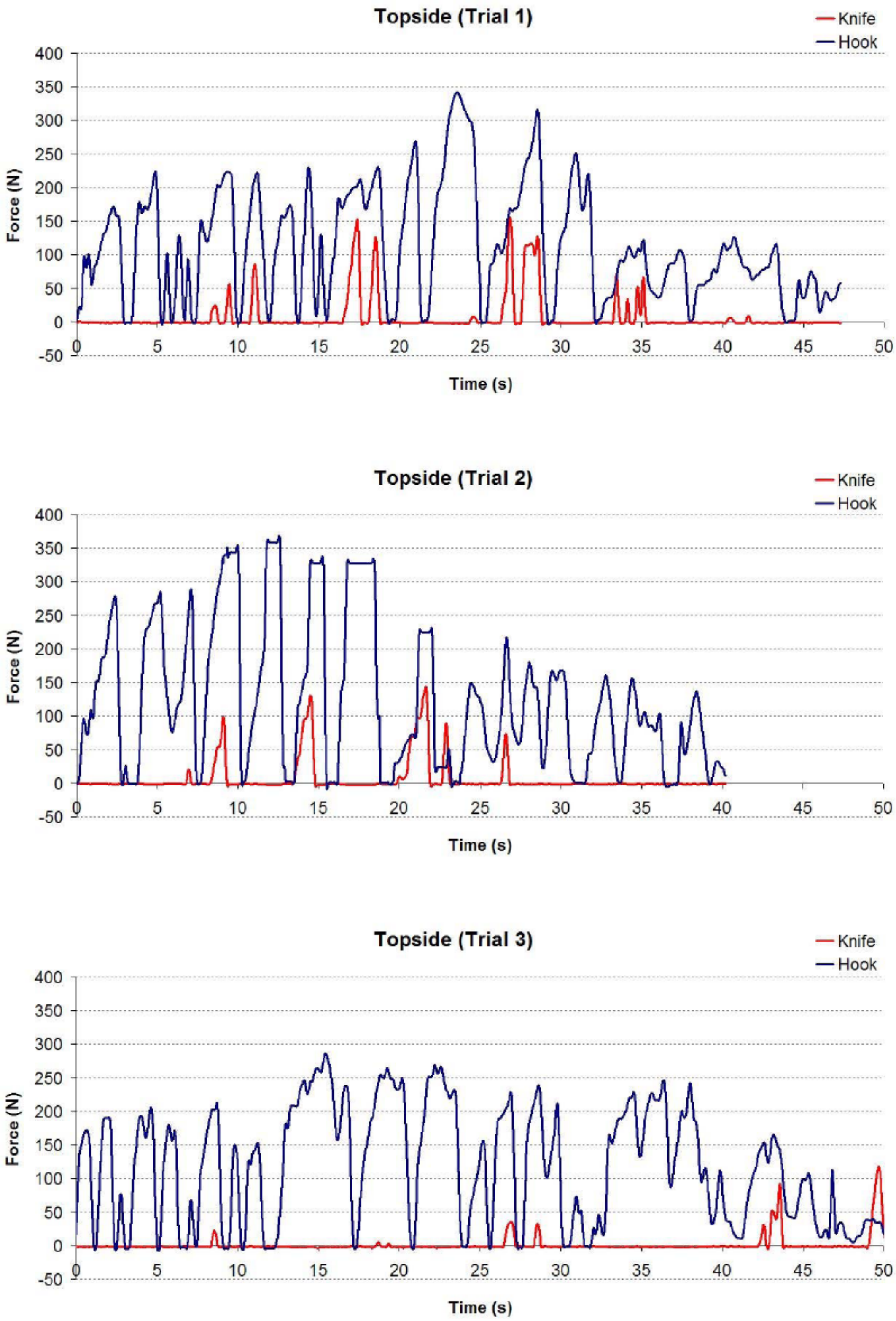


Figure A7: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the topside section.

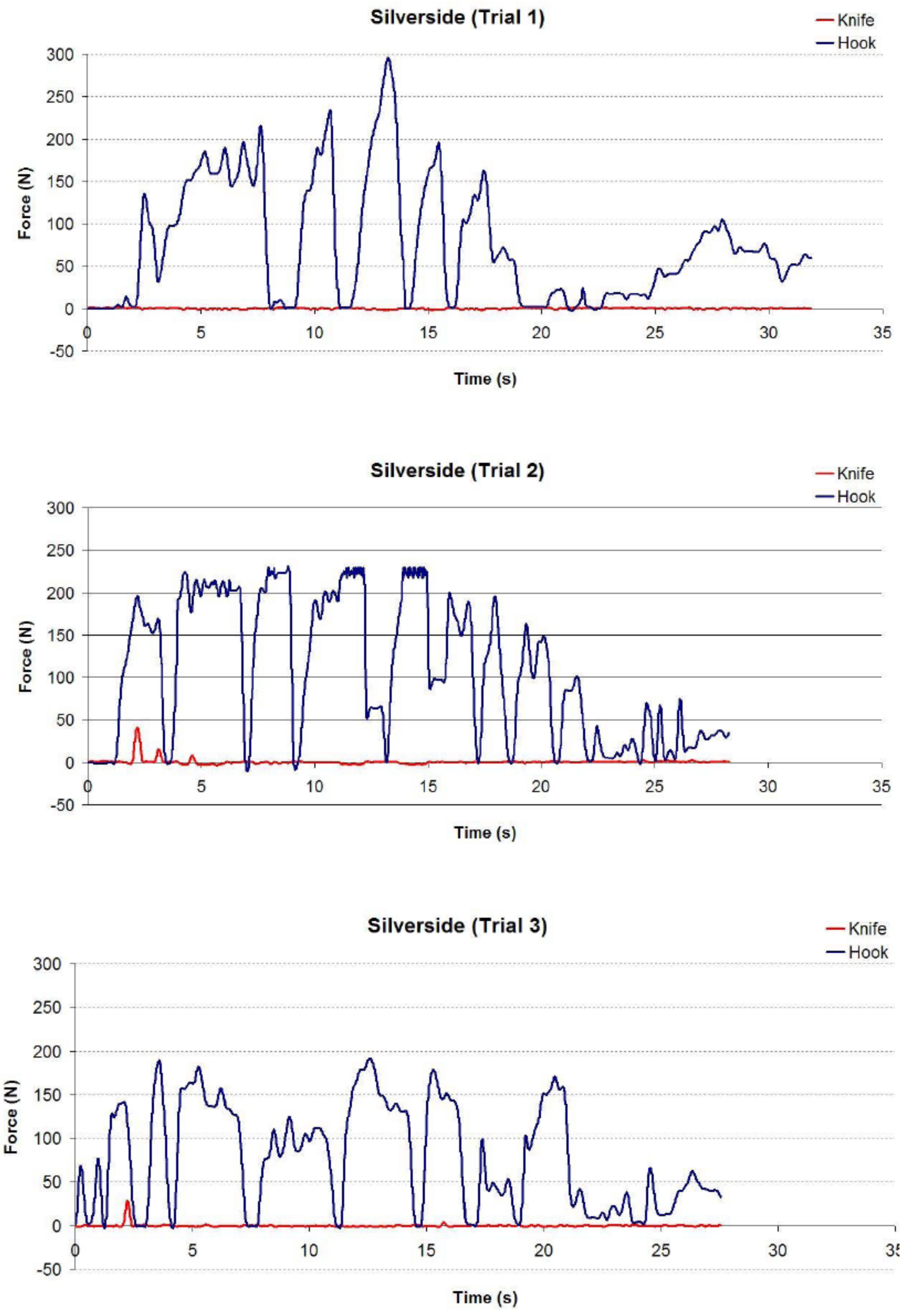


Figure A8: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the silverside section.

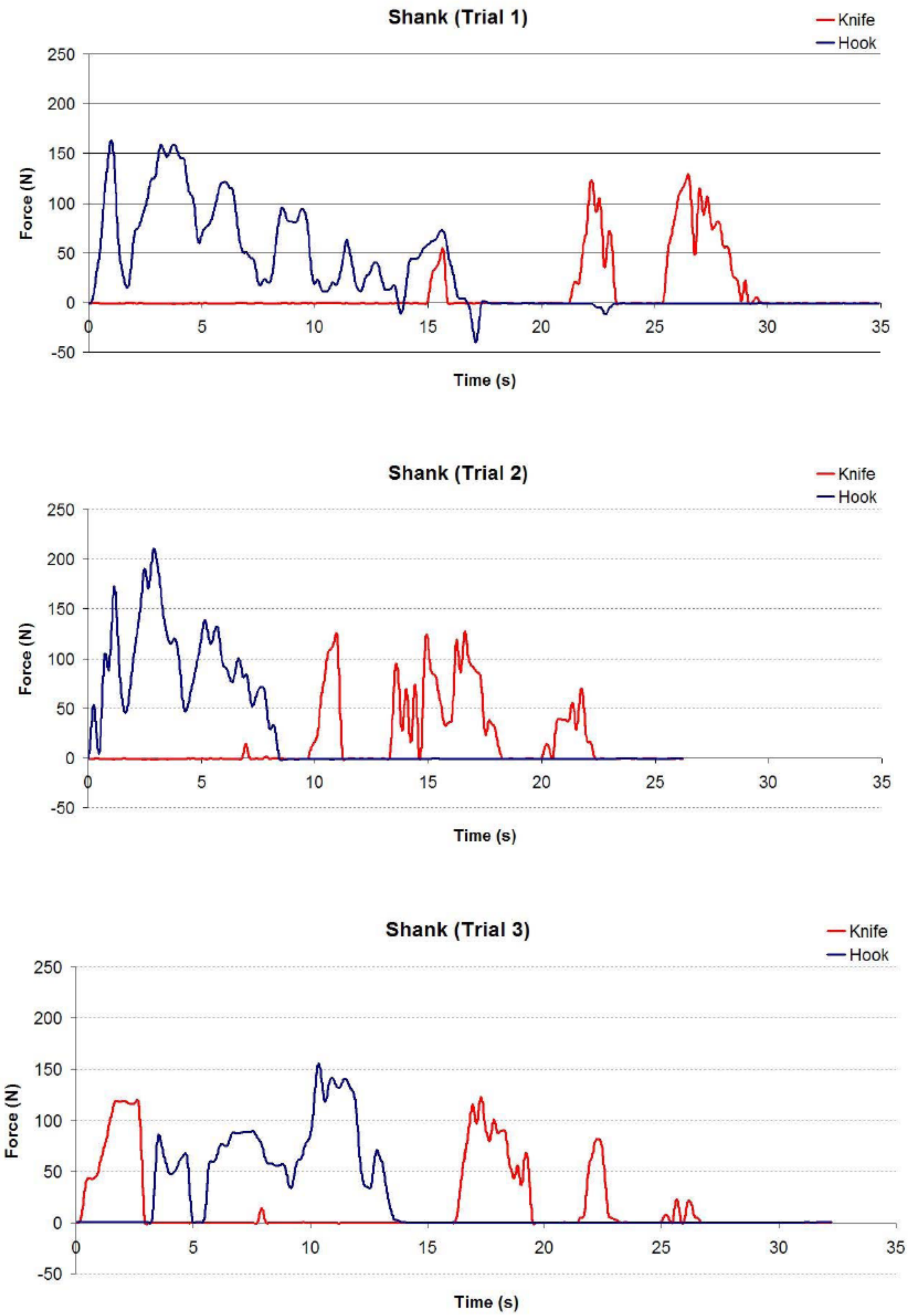


Figure A9: Kinetic hook (blue) and knife (red) forces for each carcass (trial 1, 2 and 3) whilst boning the shank section.