Proceedings of ICAD2013
The Seventh International Conference on Axiomatic Design
Worcester – June 27-28, 2013
ICAD-2013-30

A COMPARATIVE STUDY OF DECOMPOSITIONS IN AXIOMATIC DESIGN APPLIED TO SAFETY OF THE ANTERIOR CRUCIATE LIGAMENT IN ALPINE SKIING

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ABSTRACT

The objective of this work is to advance the understanding of thematic decomposition of designs for safety in the context of Axiomatic Design. Four different design solutions addressing the same safety-related customer need are compared. Special attention is given to the themes applied in the hierarchical decomposition, as well as the order in which the themes are applied. Good hierarchical decompositions are essential for the development of a well-functioning solution. The themes applied in the decomposition influence the decomposition process, and can impact the solution. Differences in the decompositions and solutions are shown. Finally, the importance of incorporating safety into the decompositions is discussed.

Keywords: thematic decomposition, ski bindings.

1 INTRODUCTION

This paper compares four different design solutions that satisfy the same safety-related customer need. The objective is to advance the understanding of thematic decomposition of designs for safety in the context of Axiomatic Design.

An important issue is the selection of an appropriate theme for the decomposition. This is important because the theme provides a basis for a assuring a collectively exhaustive and mutually exclusive decomposition [Brown, 2011]. A complete decomposition is necessary for the application of the axioms.

It has been noted that TRIZ [Altshuller, 2002] has applications in this kind of design problem. It was not used or presented to the students here. It was decided to leave it outside the scope of the current investigation.

1.1 IRAD

It has been noted in the literature that in systems where safety and functional requirements are present, performance requirements are often applied before safety requirements. This can lead to additions later on in the design process, which could complicate the design. Applying safety requirements in the conceptual stage of the design is the best way to avoid unwanted coupling and complications later in the design [Ghemraoui-Lagord *et al.,* 2011].

Innovative Risk Assessment Design (IRAD) is a method of designing safety parallel with the design of the device [Ghemraoui-Lagord *et al.,* 2011]. The designer works on task clarification, followed by development of design parameters in each of the design phases. At each stage risk is thought to be constantly evolving and dependent on the design technologies. Risks are analyzed through the design parameters, and the human interaction with them. Risks are identified, transformed into safety requirements, and then listed in the specification document. These safety requirements are then inserted at the next level of the hierarchical decomposition.

Risks can be divided into three types, corresponding to the three stages of the design. During the conceptual design stage general working principals are developed (Table 2). The risks in this stage are placed in the Human-Principal Interaction (HPI). HPI risks are defined based on the environment or the working principals of the design. They are independent of any specific solution and come from past experience. These risks become input safety objectives and act as constraints in the design [Ghemraoui-Lagord *et al.*, 2011].

This work considers a ski binding and the protection of the anterior cruciate ligament (ACL) in the knee from injurious loads that can be transmitted from the snow through the ski to the binding, to the boot, and then to the skier's leg. The function of the binding is to transmit control loads from the skier to the ski, and sensory information from the ski to the skier, and to avoid transmitting injurious loads from the ski to the skier. In this regard, it is similar to many kinds of human machine interfaces.

In the current work we note that for systems, such as ski bindings, where a primary goal is safety, input safety objectives are functional requirements in the first level of decomposition. Constraints, in this work, would be distinguished from FRs as design objectives that do not take DPs. In IRAD input safety objectives are functional requirements at the conceptual stage. At the embodiment and detail stages safety objectives consist of input constraints [Ghemraoui-Lagord *et al.,* 2011].

During the embodiment stage of the design in IRAD, the way in which the device will function is defined. Systems to carry out the working principals developed in the conceptual stage are developed (Table 2). During this stage risks are placed in the Human-System Interaction (HSI) and are related to the human activity or the existing design parameters. These risks become system safety objectives when placed in the design decomposition as functional requirements. System safety objectives are design specific. At the level of the detail stage components of the device begin to be specified (Table 2). At this stage risks fall into the Human-Machine Interaction

(HMI) and are often associated with technical design choices [Ghemraoui-Lagord *et al.,* 2011].

1.2 THEMATIC DECOMPOSITION

Decomposition is one of the ways in which Axiomatic Design facilitates designers in approaching a problem. Different themes can be applied to the decomposition, which, in-practice, arrive at different solutions, or different representations of similar solutions. The creation of a hierarchical decomposition allows designers to apply different themes at different stages of the decomposition.

Examples of general, broad themes are: temporal, spatial, energetic, and hazard based. A design can only be as good as its functional requirements [Suh, 1990]. The decomposition is the process of developing progressively lower level FRs. If a collectively exhaustive decomposition is not created at any level, the quality of the final design will be impacted. For example, a hazard based theme would only be exhaustive if all of the possible hazards could be identified [Brown, 2011]. Unidentified hazards would lead to unmitigated risks.

The prioritization of the theme can also have an effect on the number of FRs needed in the decomposition [Brown, 2011]. If for example, two themes are applied in a decomposition, the order in which they are applied may have an effect on the number of FRs. The designers should investigate different themes and prioritization of themes to ensure a collectively exhaustive decomposition with the minimum number of FRs.

1.3 SKI INJURIES AND SKI BINDINGS

Injuries to ACLs are the most common type of serious injury in alpine skiing, accounting for over 20% of all skiing injuries [Shealy *et al.,* 2003]. There are two prominent mechanisms for tearing the ACL: the Boot Induced Anterior Drawer (BIAD) [Bally *et al.,* 1989], and a combined valgus and rotation of the knee known as the "phantom foot" [St-Onge *et al.,* 2004]. This paper will focus mainly on the BIAD injury. The BIAD injury is caused by a shearing load transmitted to the knee from the stiff rear of a ski boot. This is often the result of landing after a flight in a rearward unbalanced position. Historically ski bindings do not protect the skier from ACL injury [Johnson, 1995].

Ski bindings present a special opportunity to study the interplay of performance and safety in a human-mechanical interface. A ski binding must transmit control loads to the ski while preventing injurious loads from being transferred to the skier. There are many risks which could be classified as input safety objectives, however we will focus on BIAD ACL tears for this paper. Historically, it was standard for ski bindings to release the boot from the ski when certain loads were exceeded [ASTM F939-06, 2009]. While it might seem obvious to mitigate injury by simply placing limits on the magnitude of force transmitted to the skier, it is known from experience that this strategy leads to inadvertent release, i.e., release and subsequent loss of control when injury is not imminent [Ghemraoui-Lagord *et al.,* 2011; Brown and Ettlinger, 1985]. This compromises the objective of transmitting control loads. A better decomposition, adhering to the axioms, can provide a better solution to protecting an equipment user from injury.

This paper studies the decompositions of four engineering capstone design projects addressing the customer need to reduce the risk of injury to the ACL. Only the conceptual and embodiment stages of the design will be studied. Special attention is given to the theme selected in the student's decompositions. Themes will be identified, and the order of the themes which were applied will be analyzed. The number of FRs in the decomposition will be compared along with the extent of the solutions.

2 PROJECTS

The senior capstone design projects considered here were completed between late August and mid-April. The groups were all advised by co-author Brown, who played only a passive role in the student's designs. Brown presented the problem and provided discussion on the mechanisms of injury of the ACL in skiing. Brown also provided instruction on AD. The projects were all presented to the students in April. Serious work on the decompositions began at the end of August, with the beginning of academic credit. The projects finished in April of the following year. Details of the groups can be seen in Table 1. All but the first group had access to the solutions of the previous groups.

Table 1. Details of the Groups

Group	Number of Students	Year of Completion
1	1	2006
2	1	2009
3	3	2011
4	4	2013

All of the designs were constrained to use current ski bindings, boots and skis. The groups created a separate device to be placed between the ski and the binding system. This device is called a riser plate, or binding plate, in skiing.

The groups know that ACL injuries are a consistent problem in skiing. The ACL injury becomes one of groups' input safety objectives and is an HPI [Ghemraoui-Lagord *et al.*, 2011]. The FR0s and first level functional requirements are developed from this objective. Subsequent FRs addresses the embodiment stage of the design. The design stages are defined in Table 2.

Table 2. Stages of Design [Ghemraoui-Lagord *et al.,* 2011]

Design Stage	Description of Design Stage
Conceptual	General working principals are developed
Embodiment	Systems to carry out the working principals developed in the conceptual stage are developed
Detail	Components of the device are specified

2.1 FR0

The initial functional requirements can be seen in Table 3. All of the groups addressed the customer need of a safer skiing system for protecting the ACL. Groups 1, 3, and 4 used a hazard based theme when selecting their FR0, while group 2 selected a theme based on safety in general.

Table 3. Group FR0s.

Group	FR0
1	Prevent ACL injury
2	Add safety to the Binding – Ski interface
3	Protect ACL from Injuries during skiing
4	Prevent ACL Injury while skiing

By not specifying a specific hazard group 2 opened that solution to more injuries and solutions. This makes it more difficult for the designer to form a collectively exhaustive decomposition, but a better and more complete design may be the result.

An assumption applied to the FR0 of project 1 is that it is in the context of skiing. All designs must have both skiing performance FRs and safety FRs for their decompositions to be collectively exhaustive.

2.2 SUBSEQUENT FRs

The creation of functional requirements between the initial FR0 and the *detail* design stage serves two purposes. The first is to assist in communicating the design to others. The second is to ensure that the design remains collectively exhaustive and mutually exclusive through the development of the design.

The initial FR0s are decomposed along themes. The themes guide the decompositions. Groups 1, 2, and 3 chose a spatial, load theme to segment the decomposition into control loads and injurious loads as a first step. These groups then applied different themes to each the control loads and the injurious loads in the decomposition. A work theme was applied to the injurious loads. Work was decomposed along its components, force and displacement. Through this theme the groups were able to develop a design that would absorb energy in the device that would normally be transferred to the skier, possibly causing injury. Instead of work being done on the skier's ACL, the work would be done on the plate device.

The control loads were decomposed using a location theme. Control loads transmitted though the plate device were distinguished from injurious loads transmitted to the plate device by either the ski or binding. Control loads transmitted through the plate device were then decomposed using a Cartesian theme. A flow chart showing the decomposition process can be seen in Figure 1.

Group 4 chose a spatial, Cartesian theme to decompose all of the forces in skiing as a first step. The group then applied a control load v. injurious load theme as a next step. Because the group only focused on the BIAD injury, only one direction, the y direction, was decomposed into control loads and injurious loads. The injurious loads were decomposed using a work theme, resulting in a displacement FR and a force FR. The control loads were decomposed with a moment theme, creating a FR to provide an interface for the force, and a lever arm for the force to act on. A flow chart showing the decomposition process of Group 4 can be seen in Figure 2.

The themes applied by group 4 differ in order from groups 1, 2, and 3. Four themes were still needed to reach the *detail* design phase. Furthermore, all of the groups used the same themes.

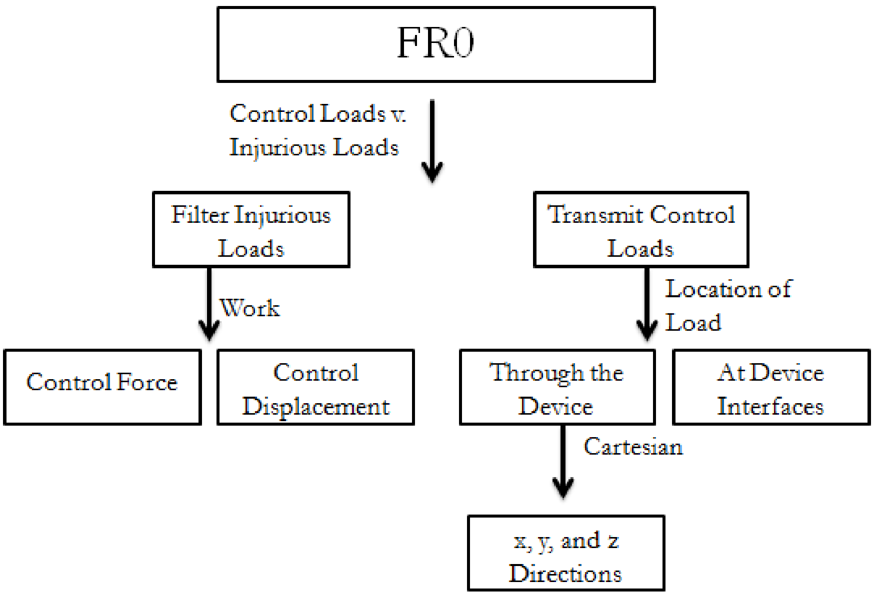

Figure 1. Decomposition flow chart for groups 1, 2, and 3. The themes are to the right of the arrows.

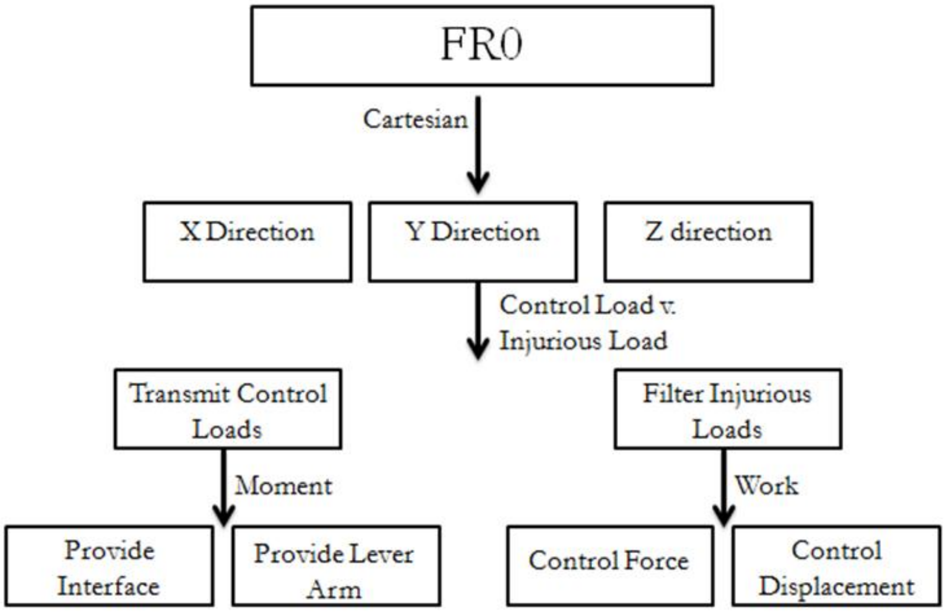

Figure 2. Decomposition flow chart for group 4. The themes are to the right of the arrows.

2.3 NUMBER OF FRS

The number of functional requirements used to reach the detailed design phase depended on how the themes were applied. Some groups combined themes together into one. Group 1 applied a control load v. injurious load theme simultaneously with a theme based on the location of the load in the system. A portion of the group's decomposition can be seen in Table 4.

Table 4. Group 1 partial decomposition

FR Number	Functional Requirement
FR 0	Prevent ACL injuries
FR 1	Allow attachment to ski and traditional binding
FR 2	Transmit normal skiing forces between ski and binding
FR 2.1	Transmit forces in x direction
FR 2.2	Transmit forces in y direction
FR 2.3	Transmit forces in z direction
FR 2.4	Transmit moments about x axis
FR 2.5	Transmit moments about y axis
FR 2.6	Transmit moments about z axis
FR 3	Filter out harmful forces
FR 3.1	Allow rotation about heel when forces are excessive
FR 3.2	Absorb Forces
FR 3.3	Allow adjustment for skiers of different weights

The number of functional requirements also depended upon when the detail stage of their decomposition began. Group 3 did not continue their decomposition far enough to apply a Cartesian theme to the control loads. The group did apply a Cartesian theme to the injurious loads, which was combined in the first step of the hierarchical decomposition with a control v. injurious load theme. A portion of group 3's decomposition can be seen in Table 5. The group created a solution which addressed both BIAD injuries and "phantom foot" injuries.

Table 5. Group 3 Partial decomposition.

FR Number	Functional Requirement
FR 0	Protect the knee from ACL injuries during skiing
FR 1	Provide an interface between binding and ski
FR 1.1	Transfer loads from binding to top plate
FR 1.2	Transfer loads from top plate to base
FR 1.3	Transfer loads from base to ski
FR 2	Provide horizontal absorption of loads during high load conditions
FR 2.1	Allow horizontal rotation about z-axis
FR 2.2	Control horizontal rotation of heel toward inside of ski
FR 3	Provide vertical absorption of loads during high load conditions
FR 3.1	Allow vertical rotation about toe
FR 3.2	Control vertical rotation of heel downwards

The numbers of FRs used to reach a solution for the BIAD injury, while transmitting control loads, are listed in Table 6. The numbers of FRs do not include FR0, and FRs pertaining to other injuries are not included.

Table 6. Number of FRs created.

Group Number	Number of FRs Created from FR0
1	13
2	12
3	7
4	13

2.4 Final Designs

All of the groups created working prototypes. These plate devices all could reduce the number of BIAD ACL injuries in skiing. These plate devices would still transmit control loads to the ski with something close to the fidelity without the plate device. The influence that these plate devices might have on performance would be limited to the added weight and height stand-off between the boot and the ski caused by the plate devices.

The plate devices are all similar conceptually. All of the plate devices absorbed the energy seen by the skier, as opposed to releasing the skier from the ski. This was accomplished by allowing the foot to rotate in the posterior direction when an injurious load is eminent. This solution is a result of applying a work based theme to their decompositions.

Differences appear at the system level in the embodiment stage of the design [Ghemraoui-Lagord *et al.,* 2011]. Three of the groups allow the heel to rotate about a point forward from the heel. Group 1 achieved the rotation with an upward rotation of the toe about a point close to the heel. The other groups absorbed the energy with a downward rotation of the heel about a point close to the toe (the location of the pivot points can be seen in Figures 3, 4, 5 and 6). This introduces coupling between the geometry and flex of the ski and the amount of energy that can be adsorbed. The design of group 1 could be said to be superior by Axioms 1 and 2. This is because the design is not coupled to the geometry of the ski beneath the plate device. It is also because the solution works in a wider range of situations, when the ski is flexed, thereby the probability of success is greater and the information content is lower. A solid model of group 1's solution can be seen in Figure 3.

All the designs with a fixed pivot will be insensitive to loads applied at the pivot point. The loads that cause BIAD injuries are applied to the rear of the ski. Therefore, when the pivot is placed further back, the probability of success is limited and the information content of the solution increases. Group two avoids a fixed pivot. The plate is able to move vertically along its length (Figure 4).

Groups 2 and 3 also incorporated components that address other injury mechanisms in their designs. Group 2 increased the work to release the heel of the boot from the binding, thereby reducing the likelihood of inadvertent releases. The design also absorbs vertical forces which can contribute to tibial plateau fractures. The designers of group number 3 incorporated a system to reduce the number of "phantom foot" ACL injuries. Images of group 2 and 3's solutions can be seen in Figures 4 and 5 respectively.

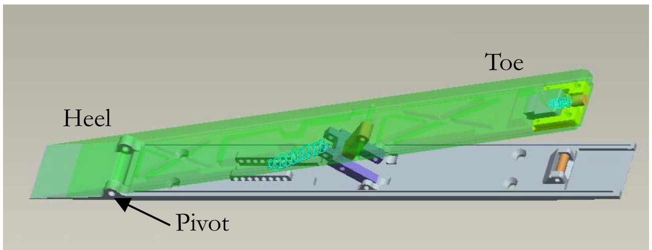

Figure 3. Group 1 final design [Miley, 2006]. The pivot point can be seen close to the heel of the plate device. The plate is seen in an open position as if the plate device has absorbed an injurious load.

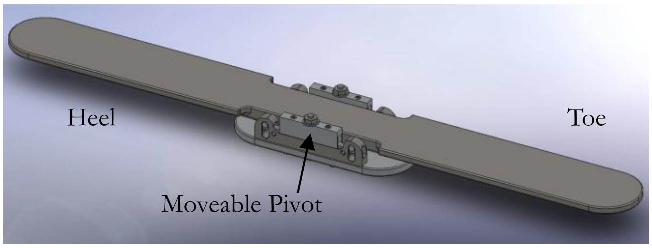

Figure 4. Group 2 final design [Havener, 2009]. The floating pivot is nominally equidistant from the toe and heel of the plate device. The plate is allowed to rotate in either the posterior or anterior direction.

Figure 5. Group 3 final design [Austin *et al.,* 2011]. The pivot point is at the toe of the plate device. The plate rotates downward at the heel about this point.

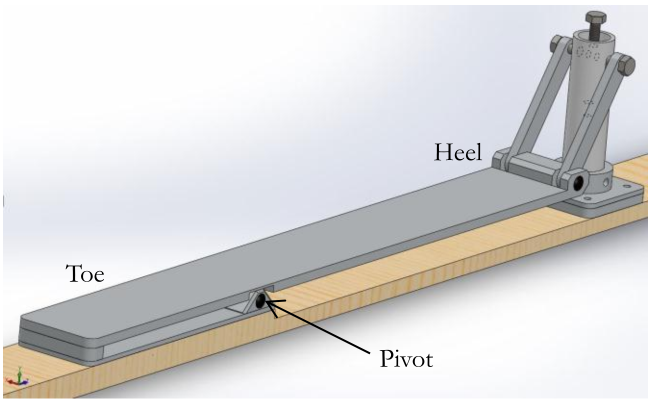

Figure 6. Group 4 final design [Bisacky *et al.,* 2013]. The pivot point is near the toe of the plate device. The plate rotates downward at the heel about this point.

3 DISCUSSION

3.1 THEMES IN SKI BINDINGS

All of the groups in this study chose spatial themes. Temporal themes were avoided by the groups. The theme most associated with the function of the device is a work theme. The three other themes used by the groups to create their solutions are the direction of the load, the location of the load in the system, and the nature of the load, i.e., whether the load is a control load or an injurious load.

The application of a work theme resulted in ski-plate-binding systems which absorbed the injurious energy. The absorption of energy was based on the direction and magnitude of the injurious force. To arrive at the solutions the groups all applied the same themes in their decompositions. The application of these themes allowed the groups to assure a collectively exhaustive and mutually exclusive decomposition.

Although temporal themes were not applied by the groups, they have been used in ski bindings. An electronic binding was developed which released the skier from the ski based on the force impulse [D'Antonio, 1984]. If an injurious force was seen by the binding, the ski boot is released from the ski only if the force had been active for a predetermined amount of time. This solution was designed to reduce the number of inadvertent releases. The ski would not be released from the skier inadvertently by a high force, if only seen for a short amount of time. It is thought that these force surges are in excess of the nominal retaining force of a mechanical work based system. These impulse loads would not be produced in a traditional mechanical system because of its compliance, which adsorb impulses or shocks. In a stiffer system with an electronic release mechanism it was found that the ski need not be released if the duration of the force is short [D'Antonio, 1984]. The solution decouples the force seen from the time duration of the force, allowing a lower release force to be specified.

The design of D'Antonio's ski binding [1984] did not address any ACL injuries, because at the time of the invention ACL injuries were not prevalent. The design addresses the problems of inadvertent release as well as leg fractures caused by excessive rotational and bending forces to the lower leg. But this does not invalidate the use of a temporal theme in the development of a system to reduce ACL injuries. The use of a temporal them could result in a good decomposition, which could produce a design solution with a good probability of success.

3.2 ORDER OF THEMES

Three of the four groups applied a theme based on the type of load in the first level of their decomposition, segmenting the decomposition immediately into control loads and injurious loads. Two of these groups applied two themes at once, either load type and direction, or load type and location in device.

Group 4 was the only group to apply a directional theme first before decomposing the loads into injurious loads and control loads. Because the group only focused on BIAD injuries, only one direction needed to be decomposed into control and injurious loads.

Table 7. Group 4 Partial Decomposition

FR Number	Functional Requirement
FR 0	Prevent ACL injury while skiing
FR 1	Transmit loads about y axis
FR 1.1	Transmit control loads about the y axis
FR 1.2	Filter BIAD ACL injury loads about y axis
FR 2	Transmit loads about x axis
FR 3	Transmit loads about z axis

The order of the themes applied in these groups did not have a large impact on the number of functional requirements created. Group 3 had fewer FRs than the other projects because they did not continue their decomposition to apply a directional theme to the control loads. It is interesting to note that in these projects, four themes were applied to reach a complete decomposition. Group 3 applied a Cartesian theme to the injurious loads, but not to the control loads. The number of themes applied was independent of the order of the themes.

It has been shown that the order of the themes applied in the decomposition can have an effect on the number of functional requirements [Brown, 2011]. When creating a functional decomposition, it is important to investigate different orders of themes to create a decomposition with the minimum number of functional requirements.

The order in which themes are applied can also have an impact on the exhaustiveness of a functional decomposition. A theme can only be useful if it can help the designer see all possible children of the parent. If all the children are not obvious, a different theme can be applied first to decompose the problem further.

3.3 CHOOSING A THEME

All groups created different solutions to the same customer need. Each final design was different from the others; however the working principles of the designs were all the same. All the designs utilized absorption of energy to eliminate injurious loads seen by the skier. This is the result of all the groups applying the same themes in their decomposition, even if in different orders.

Other themes could be applied to the decomposition of the initial customer need to create solutions acting on different working principles. It has been illustrated how the application of a temporal theme could be used to address the customer need. Designers should experiment with different themes, combinations of themes, and orders of themes during the decomposition process. Axiom 2 might be applied to choose the best solution.

3.4 IRAD AND THE PROJECTS

It is interesting to consider the IRAD system when looking at these projects. The IRAD system was developed to incorporate safety into the design of devices and systems in the early stages of design. This prevents complications of designs from the addition of safety constraints being applied late in a design. The groups here did not know about the IRAD system.

In these projects, the designers knew from experience that knee injuries were a problem in skiing, resulting in an input safety objective of preventing knee injuries. In all projects, some safety functional requirement was present in the first tier of the functional decomposition. As the groups moved through the design process risks were analyzed at each stage to form system safety objectives. These system safety objectives were dependent on the design. A common system safety objective was adjustability of the design for different weight skiers, or skiers with different size boots.

A driving factor in these designs was the safety element of the device. The designers transformed their input safety objectives into functional requirements in their decomposition. Input safety objectives can be transformed into constraints, or into functional requirements. Classifying input safety objectives as functional requirements leads to design parameters to achieve the function. Classification of input safety objectives as constraints leads to the creation of design parameters which do not compromise safety. Creation of constraints at the upper levels of decomposition influences the specification of sub-FRs, often making it more difficult to generate an acceptable set of DPs. This, in turn, can make achieving an uncoupled or decoupled design difficult [Hintersteiner, 1999].

In design problems where safety is not an important customer need, and no safety concerns are immediately obvious, safety is not often considered a functional requirement in the decomposition. But lack of safety considerations can lead to design complications. Constraints, created at the beginning will ensure the conceptual elements of the design do not place users in danger. The IRAD system can be used to incorporate safety throughout the system. Failure to incorporate safety early in the design can result in late additions to the design which may complicate the design [Ghemraoui-Lagord *et al*., 2011].

Even though these designers were unaware of the IRAD system, safety was still incorporated as functional requirements in the design decomposition. As new risks were developed based on the function of the specific solution, new safety requirements were developed and added to the decomposition. The results were devices which integrated both safety and performance. The design process of the groups was similar to the IRAD method of design. IRAD introduces a more systematic and documented strategy for incorporating safety into design. IRAD can be beneficial in large organizations or in design teams where design tasks are distributed amongst the designers, where communication of the design can become difficult. The results clearly support the IRAD model. Validation of the IRAD model would require a more directed experiment, and was not the intent of this work.

Future work on comparing design solutions could be through design contests and through the integration of similar design projects into basic curricula. These could provide controlled studies of decompositions of similar design problems using different themes. Such approaches could be the basis for a design of experiments to examine the influences of different factors more thoroughly.

3.5 IRAD AND SKI BINDINGS

When the safety ski binding was first created, ACL injuries were not common. The bindings were created without ACL injuries as an input constraint, and design parameters were developed without ACL injuries in mind. As boots got stiffer in backward lean and ACL injuries became more prevalent, designers introduced features to try to eliminate the injury. These features were added to the already existing ski binding, after the conceptual and embodiment stages of the design had been established. The result is a vertical release of the toe, which is coupled with the horizontal release of the toe. To adjust the retention force of the vertical release, the retention force of the horizontal release must be adjusted [Fischer *et al.,* 1994]. This addition of a safety feature late in the design stage has added unnecessary complexity to the design.

4 CONCLUSIONS

In the context of this work some observations can be made to facilitate the development of thematic decompositions in designs, especially those addressing safety.

1. The selection of themes facilitates the development of FRs and impacts the solutions.
2. The order of the application of themes appears to influence the number of functional requirements, the collectively exhaustive element of the functional requirement, as well as the final design.
3. Both performance and safety can be integrated into the design process consistent with collectively exhaustive and mutually exclusive criteria.

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