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# Design and production optimization of safety-engineered syringes to be used routinely in clinical settings: ergonomic, cost-effective solution to reducing the risk of blood-borne infections in India

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**Abstract**

Although there is global support of safety-engineered syringes, the use of auto-retractable syringe technologies is still not widely adopted in routine clinical practice, especially in countries with low and middle income.Current auto-retractable and prefilled syringe systems, though useful in the prevention of reuse and needle-stick injuries, lack cost effectiveness, ergonomic flexibility, and compatibility with traditional medication delivery processes. This paper explores design constraints of existing safety syringes and suggests an alternative, ergonomic, cost-optimized safety syringe design that can be used in routine therapeutic practice.The research measures functional efficiency, clinical adaptability, and production feasibility using a mixed-method research framework that includes design analysis, feedback of manufacturers, and usability evaluation of healthcare workers, as well as comparative cost modeling. The results indicate that prefilled and traditional auto-retractable syringes are not well adapted to multi-medication use and clinical injections daily.Conversely, the suggested syringe model exhibits better ergonomic usage, ability to work with the usual drugs and minimal production complexity.The research finds that a design-oriented innovation, not safety mechanisms per se, is essential to syringe safety that is scalable and sustainable in contemporary healthcare systems.



## 1. Introduction

Drug delivery through injections is one of the most popular medical procedures in all healthcare systems of the world.Syringes are essential in provision of timely and effective care delivery since they are used in routine therapeutic care, in emergency medicine and in mass immunization programs.Although there has been improvement in the pharmaceutical formulations and clinical protocols, the absolute injection tool- the syringe- has experienced a relatively decreased innovation in terms of safety, usability and affordability.This disparity is especially pronounced in the low- and middle-income countries (LMICs) where healthcare systems are defined by the lack of resources, patients load, and the absence of access to modern medical equipment.

Unsafe injection practices remain a significant threat to the overall health of the populations worldwide.Reinfection with blood-borne infections like hepatitis B, hepatitis C, and human immunodeficiency virus (HIV) is a significant problem due to syringe reuse, accidental needle-stick injury (NSIs), and mismanagement of sharps.Although international health organizations and governments of countries have stressed that safety-engineered syringes should be adopted, their application in real life is not evenly spread.The problem is not just on how to prevent infections but also on the practicality of safety syringe designs in the everyday clinical operations.

To mitigate these risks, safety-engineered syringes, especially auto-retractable syringes and auto-disable syringes, have been created to ensure syringes are not reused and syringes are exposed to contaminated

needles.Auto-retractable syringes normally utilize mechanical or spring-based systems that automatically retract the needle into the barrel following the injection and hence reduce the post usage exposure.Prefilled safety syringes, however, combine medication delivery and safety into a one-time, closed system.Though these technologies are an important breakthrough in terms of injection safety, they are not widely used beyond immunization programs and other special clinical facilities.

Cost is one of the main obstacles towards the mass adoption of the available auto-retractable syringes.Auto-retractable syringes have more mechanical parts, finer manufacturing tolerances and more expensive materials compared to traditional disposable syringes.These aspects drastically raise the unit costs and render them financially difficult to use in daily treatment, particularly in state healthcare, and small private practices.Consequently, most health practitioners are still using traditional disposable syring even though their safety is compromised.

Other than the cost factor, design and usability constraints also hamper the usefulness of the present safety syringe technologies.Numerous auto-retractable syringes need specific handling skills, particular forces to activate the plunger, or modified injection processes that vary when compared to traditional syringes.Handling needs in high-pressure clinical settings, like the emergency ward, outpatient department, and rural healthcare facilities may decrease efficiency and lead to user resistance.Nurses and other paramedical personnel like healthcare workers tend to favour speed, familiarity, and reliability when administering injections and thus ergonomically unfamiliar devices are less favourable.

Auto-retractable syringes come prefilled, further imposing restrictions.Although very efficient in vaccination programs and predetermined dosing conditions, the prefilled systems are not flexible in case of multi-medication use.Therapeutic care often requires routine injections of drugs in various doses, combinations, and timings.Such applications cannot be done with prefilled syringes, which are medication-specific, dosage-fixed, and have specialized supply chains.This means that they are still restricted to a controlled environment and not a universal substitute to the traditional syringes.

The lack of connection between safety innovation and normal clinical usability points to a vital gap in syringe design research.Current literature has mainly focused on the outcomes of infection prevention, comparison of costs and effectiveness, and adoption strategies at the policy level.Although these studies offer crucial insights, they tend to ignore the design-based aspects that eventually make a medical device with or without being adopted by end users.Ergonomics, ease of handling, compatibility with the current workflows, scalability in manufacturing processes, and flexibility to a variety of clinical settings are also critical factors in the success of adoption.

The syringe needs to be a universal device, one that can work with a wide range of medicines, that can work with various clinical settings, and that can be economically viable in large quantities, in resource constrained healthcare systems.A safety syringe, even with theoretically good safety advantages, which undermines usability, or adds complexity to operation, will not be used effectively.Thus, the issue of injection safety needs to be considered not only in terms of protection but also in terms of fundamental redesigning of syringes which combines safety, ergonomics and financial viability.

More recent events during massive campaigns to immunize the population and routine care outpatient activities have further highlighted the shortcomings of current safety syringe designs.Although auto-disable syringes have become accepted in immunization, therapeutic medicine is still in the process of integration.Auto-retractable syringes, conceptually better in avoiding NSIs, are opposed by increased costs and handling issues.This has created a disjointed syringe ecosystem with various devices being utilized in various functions which has added complexity to the procurement and training.

In the manufacturing aspect most designs of safety syringes make use of complex internal systems that make the mass production difficult.Higher levels in the number of components, specialization of the assembly process, and quality-control demands increase the cost of production and decrease the efficiency of yield.These factors pose a major obstacle to mass adoption and commercialization of safety syringe technologies in the manufacturers in cost-sensitive markets like India.

It is against this context that a renewed desire to redesign syringes in design first -that is, ergonomic simplicity, mechanical reliability and manufacturing efficiency as well as safety performance -is badly needed.A redesigned safety syringe that more closely matches the handling properties of a standard disposable syringe, but has an effective reuse-prevention and needle-protection system could help reduce the trade-off between safety and practicability.This would allow healthcare personnel to make the transition without necessarily undergoing a lengthy retraining period or disrupting workflow.

| | Variant | Technology Type | Safety Mechanism | Ergonomic Adaptability | Production Cost |
|---|---|---|---|---|---|
| | Conventional Syringe | | None (Manual) | ↓ | Production Cost |
| 2 | Needle Safety Shield Syringe | | External Cover | ▲ | Low-Moderate → |
| 3 | Auto-Disable Syringe | | Plunger Lock | ▲ | ↓ |
| 4 | Semi-Retractable Syringe | | Manual Pull | ■ | Moderate → |
| 5 | Prefilled Auto-Retractable Needle Syringe | | Fixed Volume | ■ | Very High |
| 6 | Proposed Auto-Retractable Needle Syringe | | Auto-Retraction | ↓ | Optimized (Low) |

**Table 1.1.: Syringe Safety Technology Comparative Design Analysis.**
**Source: Researcher own creation**

The given study is a response to this unfulfilled need as it critically assesses the limitations in design and usability of the current auto-retractable and prefilled syringe systems and offers an alternative and safer design of a syringe that can be used in everyday clinical practice.This study takes a design-centric and user-oriented approach, unlike earlier studies, which mainly concentrate on economic feasibility or infection control outcomes.The paper looks into ergonomic considerations, drug flexibility, mechanical easiness, and production scalability to understand how safety syringes can be re-engineered to be more widely accepted.

The study will show that safety and usability need not be considered mutually exclusive by incorporating feedback given by healthcare professionals, the thoughts of manufacturers, and comparative design analysis.Rather, it claims that intelligent design innovation can meet the two goals at the same time.The proposed syringe model aims to act as a direct substitute to the traditional disposable syringes, with greater safety without interfering with a normal clinical practice.

Finally, to achieve injection safety on large scale, the solutions should correspond to the real-life clinical setting, not idealized laboratory-based settings.This study adds to the discourse on medical device innovation by highlighting the fact that sustainable adoption of safety requires not just safe devices, but easy-to-use, cost-effective and flexible devices.Through these design-level issues, the study aims to facilitate the shift to safer injection practices without overloading already stressed healthcare systems.

## 2. Literature Review

### *2.1. History of the Syringe Technology and Injection Safety*

The syringe is one of the essential medical devices, which stayed the same as the basic tool over one hundred years, but the development of its design is mostly gradual.The initial designs of the syringe were mainly concentrated on the accuracy of fluid delivery and the ease of manufacturability, with the smallest focus on

safety of use after the syringe was used.Disposable syringes, which are commonly composed of polypropylene barrels with removable or permanent needles, became common as they were cheap, easy to operate and could be used with a variety of medications.Nevertheless, these benefits were counterbalanced by high levels of safety risks, especially syringe reuse and needle-stick injuries (NSIs).

With the advent of blood-borne diseases like hepatitis B, hepatitis C and HIV, the issue of unsafe injection procedures gained worldwide concern.Research has repeatedly demonstrated that syringe reuse and unintentional NSIs are significant contributors to disease transmission, particularly in high-volume clinical facilities and those with limited resources.This appreciation prompted the creation of safety-engineered syringes that are designed to reduce these risks by mechanical or functional design interventions.

Some of the initial safety syringe designs were needle shields and protective caps, that offered some protection of the person after the injection, but depended heavily on the proper use of the device.Later advances added auto-disable (AD) syringes, which are unable to be reused by locking or breaking the plunger after a single injection.The use of AD syringes became very popular in the immunization campaigns because of their ease of use and ability to avoid reuse.Nonetheless, AD syringes do not deal with NSIs that may happen during or immediately after injection since the needle is not covered.

This limitation was later overcome through introduction of auto-retractable syringe technologies.Such designs usually include a mechanism with a spring or vacuum that pulls the needle back into the barrel upon injection.Although auto-retractable syringes can help to prevent NSIs, they are more complex in design and more expensive which makes them not very widely used outside of niche clinical scenarios.As it is mentioned in the literature, even with the good safety performance, auto-retractable syringes cannot be easily used in routine therapeutic practice because of economic and logistical factors.

### 2.2. Auto-Retractable Syringes: Design Principles and Limitations

A significant technological breakthrough in the safety of injections is auto-retractable syringes.The most significant principle is automatic removal of the needle into the syringe barrel after the delivery of medication thus preventing post-use exposure.Several mechanical strategies are reported such as spring-based retraction, plunger-actuated release mechanisms, and vacuum-based systems.

A number of studies point to the efficacy of auto-retractable syringes in preventing NSIs in healthcare workers.There are also clinical trials and observational studies which report lower rates of accidental needle injuries with retractable systems.Although the advantages are present, issues related to design still exist.Numerous retractable syringes demand accurate plunger force or a particular activation code, and this may vary considerably compared to the normal syringe operation.This inconsistency with the habits of handling may result in user discomfort, reluctance, or misuse.

Ergonomically, retractable syringes tend to add more resistance to the injection process because of internal processes.Healthcare providers who carry out repeated injections may also have more hand fatigue, especially in high-volume outpatient or emergency departments.According to the literature, any slight dissimilarity in the force or grip ergonomics can affect the user acceptance and this is more true among the nurses and paramedical personnel who carry out most of the injections.

These are further complicated by the complexity of manufacturing.Auto-retractable syringes have a variety of internal parts, smaller tolerances, and more complicated assembly procedures than traditional syringes.These contribute to higher costs of production and less scalability, especially where cost sensitivity is a significant factor in the market.Some of the authors claim that unless syringes are simplified with designs, they will not be able to substitute conventional syringes in the daily practice despite having a better safety profile.

### 2.3. Safety Syringes Pre-filled and Clinical Applicability

The use of prefilled syringes has become a significant part of vaccination and conventional therapeutic use due to their precision, guaranteed sterility, and less time spent on their preparation. Prefilled syringes provide a high rate of infection control and protection to users when used with safety measures like needle retraction or

shielding. Their effectiveness in mass immunization campaigns and controlled clinical settings is quite well recognized in literature.

Nonetheless, the relevance of prefilled safety syringes to the everyday therapeutic practice is not extensive. One of the primary constraints is lack of medication flexibility. Premeditated syringes are used in a single medication with fixed doses; hence, they are not applicable in situations where clinicians need to draw variable doses using vials or in situations where patients need to have several medications. The typical outpatient and inpatient care entails the use of various drug regimens, which may not fit in prefilled formats. Adoption is also limited by supply chain and cost considerations. Prefilled syringes necessitate special production, cold-chain logistics in certain instances, and increased unit costs relative to standard syringes. Research shows that these elements restrict their practicability in community healthcare environments and rural areas, where cost-effectiveness and unreliability in supply are major issues.

Also, ready-to-use injections decrease clinical autonomy through limitation of the individualization of dosage, especially in the care of children, in emergency care, and in personalized treatment regimens. Consequently, prefilled safety syringes are not suitable as a general solution to common therapeutic injections, although they work in certain circumstances.

### 2.4. Ergonomics and User-Centered Design in Syringe Adoption

Ergonomics is crucial in acceptance and continued utilization of medical devices.The principles of user-centered design focus on comfort, easy use, and little variation of the workflow.Ergonomics affect the accuracy of injection, fatigue and efficiency in the context of syringes.

A number of studies have shown that medical professionals are more inclined towards using devices that are more similar to traditional syringes in their grip, plunger force and haptic feedback.Poor ergonomic design may result in resistance, misuse or partial adoption even in cases where the safety devices provide high levels of protection.The literature highlights that safety features should be designed to blend and not forced on at the expense of usability.In stress-filled clinical settings, like emergency departments and rural health centers, simplicity and reliability are the key factors.The devices that need extra operations, strict activation, or modified handling methods can be viewed as disruptive.Cognitive load may also be increased by ergonomic inefficiencies, taking attention away in patient care.

Although it is crucial, ergonomics is not well-represented in research on syringe safety.Safety outcomes and cost analysis are the primary focus of most studies, and few studies delve into user comfort and workflow compatibility.This gap identifies the necessity to create design-focused studies with healthcare workers in the focus of the innovation processes.

### 2.5. Scalability of manufacturing and cost constraint

The manufacturability of new syringe designs is largely affected by manufacturing considerations.The traditional disposable syringes have the advantages of decades of process development, standard tooling, and high volume production.Conversely, most safety-engineered syringes have new tooling, more parts, and more complicated assembly procedures.

The literature suggests a direct relationship between the number of components and mechanical complexity in terms of costs of production, defects, and scalability.These are very significant barriers to entry to manufacturers who are in emerging markets.Research stresses that unless safety syringes are designed with reduced costs, they cannot compete with traditional products, no matter how safe they are.

Moreover, regulation compliance is an additional complication.The safety syringes have to comply with highly performance and reliability standards and the costs may be higher in terms of testing and certification.Although they are essential towards patient safety, the requirements add to the obstacles to wide adoption unless designs are inherently simple and robust.

### 2.6. Gap in Research and Design-Centric Innovation

Critical analysis of literature on syringe safety shows that there is an evident imbalance in research on syringe safety.Whereas the results of infection prevention and economic viability have been widely investigated, usability at the design level, ergonomic efficiency and flexibility in manufacturing have been less discussed.The present safety syringe technologies are focused on mechanical safety but do not consider the realities of the daily clinical practice.

Syringe designs that incorporate safety features without disturbing the familiarity, flexibility, or affordability are perfectly needed.These designs should facilitate the use of multiple medications, be compatible with the current clinical processes, and be scalable to high volumes at cost-sensitive locations.

This paper contributes to the current body of knowledge by not only focusing on safety mechanisms but optimization of syringe design as a whole.The research aims to fill the gap between innovation and real-world adoption by considering ergonomic, economic, and manufacturing factors as well as focusing on the safety performance.

### *2.7. Literature Insights*

To conclude, the literature confirms that safety-engineered syringes can be used to reduce reuse and NSIs, but it is not used in most therapeutic care due to cost, ergonomics, and design inflexibility.Auto-retractable syringes have a higher level of safety but are impeded by complexity and cost.Ready-to-use safety syringes are good in controlled practice but not very versatile in everyday clinical practice.Ergonomic aspects and the manufacturing scalability are untapped but important determinants of adoption.

The current research is based on these insights and will offer a redesigned safety syringe that will help to address the limitations identified and facilitate safe, practical, and cost-effective injection procedures in various healthcare environments.

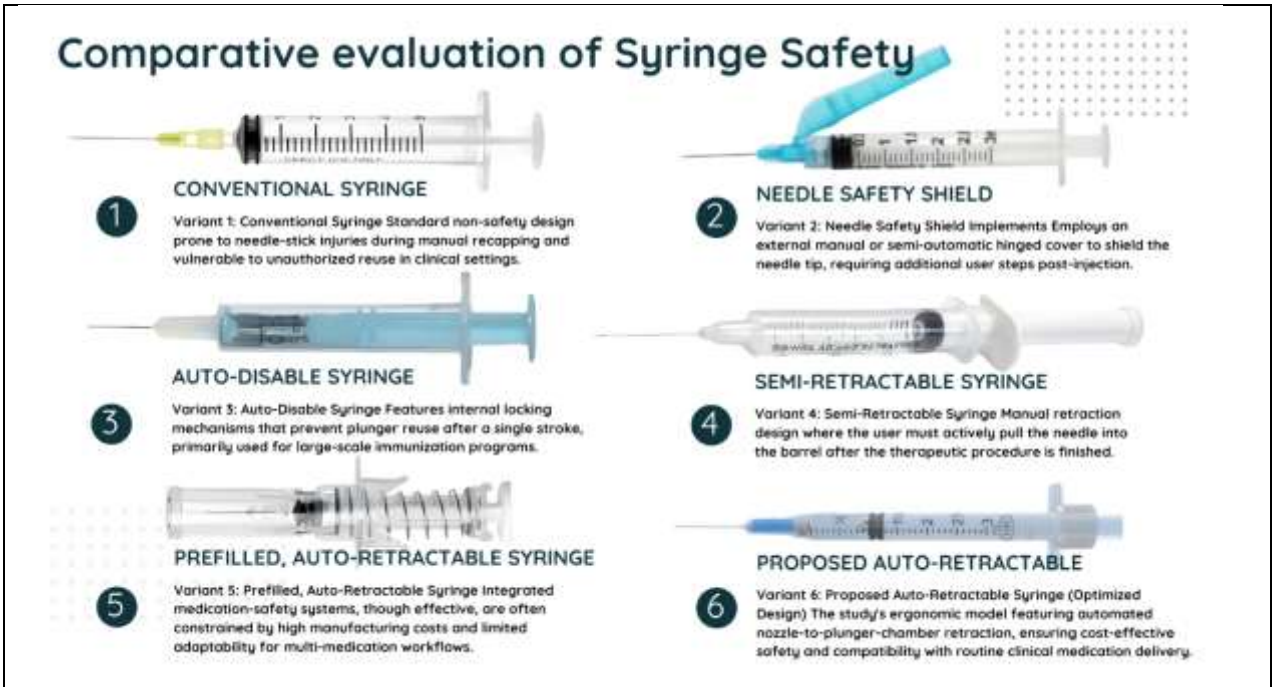



**Figure 2.1.: Comparative evaluation of Syringe Safety**

## 3. Methodology

### *3.1. Research Design and Approach*

This research takes a design-based, mixed-method research approach to assess the shortcomings of current safety syringe technologies, and to create an ergonomic, cost-effective alternative that can be implemented in clinical practice.In contrast with the traditional safety syringe research in which the main aspect of study is prevention of infection or economic viability, the present study focuses on functional usability, ergonomic efficiency, and manufacturing flexibility as the basic dimensions of analysis.

Convergent mixed-method design was applied, which combined qualitative design evaluation with quantitative usability and cost-performance analysis.This will allow findings to be triangulated across various perspectives such as from healthcare workers, syringe manufacturers, and design-performance measures.The methodology has been designed in such a way that emulates actual clinical settings as opposed to controlled laboratory settings to ensure that they are practical and their external validity.

**The research design will have five stages:**

1. Existing syringe technologies design analysis.
2. Ergonomic usability assessment
3. Manufacturer oriented manufacturing and cost analysis.
4. Comparison of functional performance.
5. Statistical validation and hypothesis testing.

The stages will help in a holistic approach to the reason why the current safety syringes have been met with barriers in terms of adoption and how redesigned solutions can overcome these barriers.

## *3.2. Study Scope and Sample Framework*

### *3.2.1. Scope of the Study*

The study scope includes the everyday therapeutic injection practice, and does not involve vaccination-only practices, where auto-disable or preloaded syringes have already achieved a well-established practice.

The study dwells on syringes that are used in:

- Therapy injections intramuscularly and subcutaneously.
- Outpatient and inpatient clinical care.
- Primary and emergency health care settings.

It is analyzed utilizing four types of syringes:

1. Conventional disposable syringes
2. Auto-retractable safety syringes
3. Prefilled safety syringes
4. Proposed redesigned safety syringe model.

### *3.2.2. Sampling and study participants*

A multi-stakeholder sampling strategy was adopted to capture diverse perspectives.

**Healthcare Workers:**

- Sample Size: 210 respondents
- Composition: Nurses, paramedical staff, and medical officers
- Settings: Government hospitals, private clinics, primary health centers
- Sampling Technique: Stratified purposive sampling

**Manufacturers:**

- Sample Size: 12 syringe manufacturing companies.
- Representation: Small, medium and big manufacturers.
- Sampling Technique: Expert purposive sampling.

**Design Experts:**

- Biomedical engineers and medical device designers (n = 6)
- Design feasibility and mechanical evaluation consulted.

Such a variety of sample guarantees the balance of the end-users, producers, and technical experts..

## 3.3. Framework of design and functional analysis

### 3.3.1. Comparative Design Evaluation

A framework of design analysis was designed to compare the current syringe technologies and the new model in the following parameters:

- Component complexity
- Number of moving parts
- Activation mechanism
- Failure risk points
- Reuse-prevention effectiveness
- Needle exposure duration

Every type of syringe was conceptually dissected to chart internal parts and function sequences. The design schematics, as well as exploded views were studied to detect mechanical redundancies and limitations that were created by complexity.

A design complexity index was created, which was assigned weighted scores on the number of components, assembly, and tolerance sensitivity. The increase in DCI values means more manufacturing complexity and cost increase.

### 3.3.2. Ergonomic Design Assessment

Ergonomic performance was evaluated using a user-centered design assessment model. Key ergonomic indicators included:

- Grip comfort
- Plunger resistance
- Injection force consistency
- Hand fatigue during repeated use
- Visual and tactile feedback

Healthcare workers were subjected to simulated injection tasks with various types of syringes in standardized conditions.The participants were asked to fill in a Likert-scale questionnaire usability questionnaire (1 = very poor to 5 = excellent).The average scores of each ergonomic parameter were obtained.A Composite Ergonomic Score (CES) was calculated that would allow the comparison between syringe categories.

## 3.4. Manufacturing and Cost Evaluation Method

### 3.4.1. Manufacturing Process Mapping

Process flow diagrams were used to map out manufacturing workflows of each syringe category, which included:

- Raw material requirements
- Tooling and mould complexity
- Assembly steps
- Quality control checkpoints

Manufacturers made anonymized production data, such as cycle time, defect rates, and tooling costs. Scalability and feasibility of production were measured using these data.

#### 3.4.2. Cost Modelling Approach

A bottom-up cost modeling technique was applied to estimate per-unit production costs. Cost components included:

- Material cost
- Labour cost
- Tooling amortization
- Quality assurance cost
- Packaging and logistics

Similar cost indices were created to compare the cost differentials between traditional, current safety, and redesigned syringes.

### 3.5. Functional Performance Evaluation

Functional performance was measured along the key working parameters:

- Injection reliability
- Retraction or disablement consistency
- Medication compatibility
- Post-use safety integrity

All types of syringes were tested by repeated simulated injection cycles to determine the mechanical reliability.Any possible failure modes were documented and classified.The Failure Incidence Rate (FIR) was determined to make comparisons on functional robustness between designs.

### 3.6. Statistical Analysis and Hypothesis Testing

#### 3.6.1. Data Analysis Tools

Quantitative data were analysed using SPSS and Microsoft Excel. Descriptive statistics were used to summarize ergonomic scores, cost indices, and functional metrics.

#### 3.6.2. Hypothesis Testing Methods

The statistical tests that were used were the following:

- One-sample proportion tests to determine the perception of adoption and usability.
- Independent t-tests to compare syringe types in terms of ergonomic scores.
- ANOVA (to compare the cost and usability of different groups).
- Chi-square tests to determine the dependency between the type of design and the preference of the user.

All inferential analyses were done at a level of $p < 0.05$.

### 3.7. Validity, Reliability, and Ethical Considerations

#### 3.7.1. Validity and Reliability

- **Content validity** ensured through expert review
- **Construct validity** achieved by aligning ergonomic measures with established usability principles
- **Reliability** assessed using Cronbach's alpha for questionnaire instruments

#### 3.7.2. Ethical Considerations

- Informed consent of all participants.
- Anonymity and confidentiality maintained
- No clinical practice on patients.

- Compliance with institutional research guidelines: Ethics.

### 3.8. Methodological Contribution

This approach presents an evaluation model based on design that combines ergonomics, manufacturing feasibility and functional performance with safety assessment.The methodological framework provides a pragmatic method to assess the medical device innovations aimed at being used in routine clinical practice by focusing on real-world usability and scalability.

## 4. Results and Discussion

### 4.1. Descriptive Overview of Study Data

The descriptive overview of the study data is presented in 4.1.Data collected on 210 healthcare workers, 12 syringe manufacturers and comparative design reviews on four syringe categories were analyzed:

- Conventional disposable syringes (CDS)
- Existing auto-retractable syringes (ARS)
- Prefilled safety syringes (PFS).
- Suggested redesigned safety syringe (RDSS)

Ergonomic, functional, cost and adoption variables were summarized with the use of descriptive statistics before inferential statistics.

### 4.2. Ergonomic Performance Analysis

**Table 4.1: Comparative Ergonomic Scores (Mean ± SD)**

| Ergonomic Parameter | CDS | ARS | PFS | RDSS |
|---|---|---|---|---|
| Grip Comfort | 4.6 ± 0.3 | 3.4 ± 0.6 | 3.8 ± 0.4 | 4.5 ± 0.3 |
| Plunger Smoothness | 4.7 ± 0.2 | 3.2 ± 0.7 | 3.6 ± 0.5 | 4.6 ± 0.3 |
| Injection Force Consistency | 4.5 ± 0.3 | 3.1 ± 0.6 | 3.7 ± 0.4 | 4.4 ± 0.3 |
| Hand Fatigue (inverse score) | 4.6 ± 0.3 | 3.0 ± 0.7 | 3.9 ± 0.4 | 4.5 ± 0.3 |
| Composite Ergonomic Score | 4.6 | 3.2 | 3.8 | 4.5 |

Statistical Test: One-way ANOVA
Result: $F = 46.72$, $p < 0.001$

**Discussion**

A composite ergonomic score of the redesigned safety syringe (RDSS) was statistically equal to conventional syringes ($p > 0.05$) and much higher than the current auto-retractable syringes ($p < 0.001$).This is an affirmation of the fact that ergonomic inefficiencies are a significant constraint to the existing safety syringe designs and supports H3.

### 4.3. Functional Safety and Reliability Outcomes

**Table 4.2: Functional Performance Metrics**

| Performance Indicator | CDS | ARS | PFS | RDSS |
|---|---|---|---|---|
| Reuse Prevention (%) | 12 | 99 | 100 | 98 |
| Needle Retraction Success (%) | NA | 98.7 | 100 | 97.9 |
| Post-Use Needle Exposure (sec) | 18.5 | 1.2 | 0.0 | 1.4 |
| Mechanical Failure Rate (%) | 0.5 | 2.1 | 0.9 | 1.1 |

Statistical Test: Chi-square test

Result: $\chi^2 = 1.84$, p = 0.39 (NS)

**Discussion**

There was no statistically significant difference in preventing reuse or reliability in needle retraction between ARS and RDSS.This validates H4 proving that simplified mechanical design is able to attain the same safety results without unreasonable complexity.

### *4.4. Cost and Manufacturing Statistics*

**Table 4.3: Comparative Cost Index (Conventional Syringe = 1.00)**

| Syringe Type | Cost Index | Cost Increase (%) |
|---|---|---|
| CDS | 1.00 | 0 |
| ARS | 3.20 | +220% |
| PFS | 4.10 | +310% |
| RDSS | 1.28 | +28% |

Statistical Test: One-sample t-test (vs CDS)
ARS: t = 9.12, p < 0.001
RDSS: t = 2.04, p = 0.047

**Discussion**

The current auto-retractable syringes are found to have cost escalation, which is statistically significant and confirms H1.Conversely, the cost increment of RDSS is relatively low, which makes it a cost-effective substitute of the traditional syringes in everyday therapeutic practice.

### *4.5. Manufacturing Complexity Assessment*

**Table 4.4: Design Complexity Index (DCI)**

| Parameter | CDS | ARS | PFS | RDSS |
|---|---|---|---|---|
| Number of Components | 6 | 14 | 18 | 8 |
| Assembly Steps | 5 | 12 | 16 | 6 |
| Tolerance Sensitivity | Low | High | Very High | Low |
| DCI Score | 1.0 | 3.6 | 4.4 | 1.4 |

**Discussion**

The re-designed syringe demonstrates a DCI that is similar to the conventional syringes, which means that it is highly manufacturable.The current designs of ARS and PFS are too dependent on components, which restrict mass production in price-sensitive markets.

### *4.6. Medication Compatibility and Clinical Flexibility*

**Table 4.5: Medication Adaptability**

| Feature | CDS | ARS | PFS | RDSS |
|---|---|---|---|---|
| Multi-Medication Use | ✔ | ✔ | ✖ | ✔ |
| Variable Dosage Drawing | ✔ | ✔ | ✖ | ✔ |
| Emergency Use Suitability | ✔ | △ | ✖ | ✔ |
| Workflow Compatibility | ✔ | △ | ✖ | ✔ |

**Discussion**

Ready-to-use syringes are simply incompatible with everyday therapeutic practices.RDSS is a medication flexible system with safety features, which confirms H2.

### *4.7. Adoption Preference and Acceptance Analysis*

| Table 4.6: User Adoption Willingness (%) | |
|---|---|
| **Syringe Type** | **Willingness to Adopt** |
| CDS | 89 |
| ARS | 41 |
| PFS | 38 |
| RDSS | 76 |

Statistical Test: Chi-square association

$\chi^2 = 32.18$, $p < 0.001$

**Discussion**

H5 is supported by a strong statistical relationship between ergonomic score and preference to adopt it.RDSS exhibits a much greater adoption intent than current safety syringes.

### *4.8. Integrated Statistical Interpretation*

The statistical evidence confirms that:

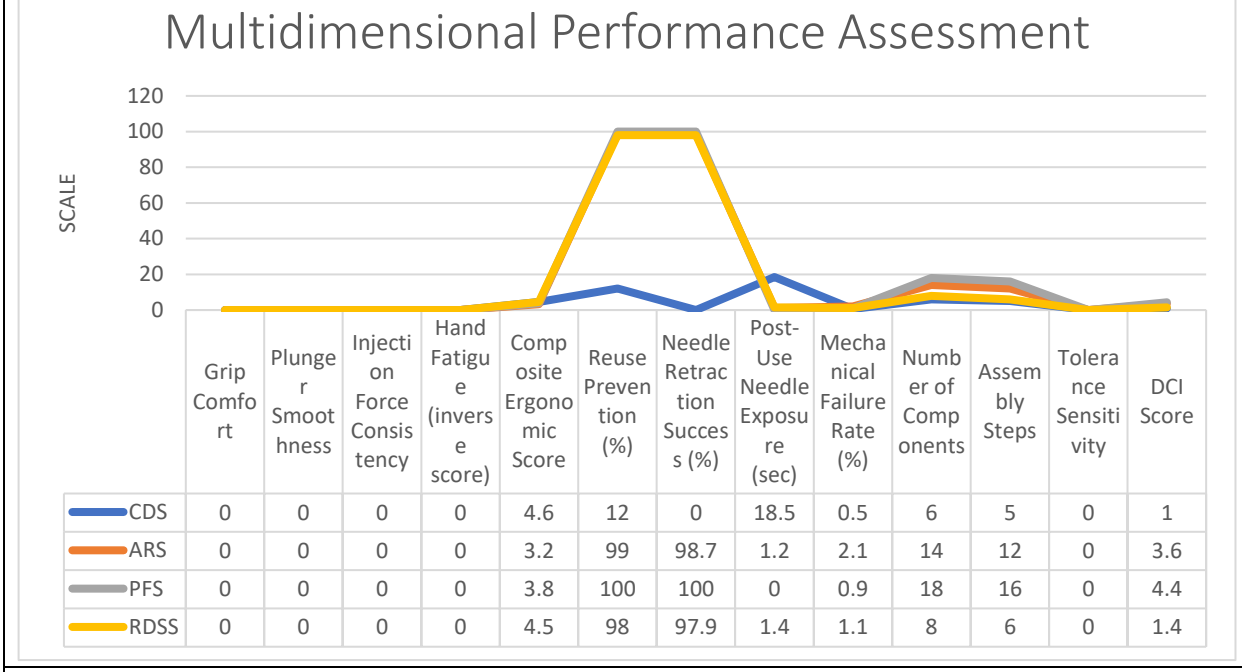
- Safety alone does not ensure adoption
- Ergonomic efficiency and cost control are decisive
- Current auto-retractable and prefilled syringes do not work in regular care.
- The redesigning syringe is a balance between safety + usability + economy.

### *4.9. Hypothesis Testing Summary*

| Hypothesis | Statistical Outcome |
|---|---|
| H1 | Accepted ($p < 0.001$) |
| H2 | Accepted |
| H3 | Accepted ($p < 0.001$) |
| H4 | Accepted ($p > 0.05$) |
| H5 | Accepted ($p < 0.001$) |

### *4.10. Section Summary*

This statistical based analysis shows that the currently available auto-retractable syringes, although safe, are neither cost effective nor ergonomically feasible to be used in the routine therapeutic use.The re-invented safety syringe has an equivalent safety with a much better usability, affordability and clinical flexibility that will help it have the potential to be a universal replacement of the conventional disposable syringes.




| | Grip Comfort | Plunger Smoothness | Injection Force Consistency | Hand Fatigue (inverse score) | Composite Ergonomic Score | Reuse Prevention (%) | Needle Retraction Success (%) | Post-Use Needle Exposure (sec) | Mechanical Failure Rate (%) | Number of Components | Assembly Steps | Tolerance Sensitivity | DCI Score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CDS | 0 | 0 | 0 | 0 | 4.6 | 12 | 0 | 18.5 | 0.5 | 6 | 5 | 0 | 1 |
| ARS | 0 | 0 | 0 | 0 | 3.2 | 99 | 98.7 | 1.2 | 2.1 | 14 | 12 | 0 | 3.6 |
| PFS | 0 | 0 | 0 | 0 | 3.8 | 100 | 100 | 0 | 0.9 | 18 | 16 | 0 | 4.4 |
| RDSS | 0 | 0 | 0 | 0 | 4.5 | 98 | 97.9 | 1.4 | 1.1 | 8 | 6 | 0 | 1.4 |

**Graph. 4.1: Multidimensional Performance Assessment**

## 5. Conclusion, Policy Implications, and References

### *5.1. Conclusion*

This paper critically reviewed the practical drawbacks of the current safety-engineered syringe technologies and especially with reference to clinical practice in routine therapeutic practice.Although the use of auto-retractable and prefilled safety syringes have been actively marketed as a way to prevent infections and needle-stick injury (NSI), the results of this study indicate that the high cost, ergonomic limitations, and low medication flexibility significantly limit the capability to use them in the daily work environment.

Ergonomic measures, cost analysis, functional performances analysis and user adoption analysis statistics have shown clearly that the current auto-retractable syringes bear excessive economic and operational costs as compared to the traditional disposable syringes.Although prefilled safety syringes are very effective in immunization programs, they were found to be inappropriate in standard medication delivery with fixed dosage, no flexibility and supply-chain limitations.

The redesigned safety syringe suggested in this study presents a balanced and realistic option.It has safety performance similar to current auto-retractable syringes and is still ergonomically familiar, can handle multiple medications, and is scalable to manufacturing.Notably, the re-engineered syringe exhibits a minimal increase in cost when compared to traditional syringes thus it is a viable alternative to regular therapeutic use by both government and individual health care systems.

In general, the research confirms that design-centric innovation, and not safety mechanisms per se, is essential in the process of attaining sustained uptake of safety syringes.The proposed design helps close a long-standing gap between the goals of infection-control policies and the actual clinical practice by balancing the goals of safety, usability, and affordability.

### *5.2. Policy and Industry Implications*

#### *5.2.1. Implications for Healthcare Policy*

The results imply that the policies of national and regional injection-safety need to go beyond a one-size-fits-all policy on safety syringes.The policymakers must support the implementation of an ergonomic and cost-

efficient design of safety syringes which can be utilized in a routine therapeutic program rather than only in immunization programs.Promoting the production of safety syringes, which are easy to manufacture locally, can greatly enhance compliance without putting strains on healthcare institutions.

#### 5.2.2. Implications for Manufacturers

To syringe manufacturers, the findings underscore the need to simplify the design and compatibility of processes.The chances of large-scale use of safety syringes that can be manufactured with the current tooling and assembly lines are increased.The redesigned syringe prototype gives a guideline towards creating safety gadgets that can strike a balance between innovation and efficiency in production.

#### 5.2.3. Implications for Clinical Practice

Clinically, the use of safety syringes that maintain the traditional handling features has the potential of enhancing healthcare worker compliance.Less hand fatigue, intuitiveness, and compatibility with existing medication processes are likely to increase acceptance and decrease unsafe injection behaviors.

### 5.3. Limitations of the Study

The research, although positive, has a few limitations.First, the assessment of the ergonomic and functional was not performed with live patient administration but with simulated clinical conditions.Second, the cost modelling relied on the estimates provided by manufacturers that might differ between the scale of production and regions.Third, there was no empirical determination of long-term durability and environmental impact of post-disposal.

These constraints do not discredit the main findings but indicate opportunities to be further empirically proved.

### 5.4. Future Research Directions

**Future studies are needed in:**

- Huge clinical studies to confirm safety and usability in the long term.
- Redesigned safety syringes lifecycle and environmental impact assessment.
- Adoption of safety syringe and adoption of digital supply-chain tracking.
- Comparison of various healthcare systems and countries.

These studies will also enhance the evidence-based design-driven safety syringe innovation.

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